TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

The Federal Register of July 14, 2000 (Vol. 65, No. 136, pgs. 43800-43802) announced the formation of a new Aviation Rulemaking Advisory Committee (ARAC) with a "Tasking Statement" covering the formation of an Aircraft Fuel Tank Inerting Harmonization Working Group.

The tasking statement requested that the ARAC provide, among other tasks, methods of introducing nitrogen gas into the affected airplane fuel tanks to displace the oxygen in the ullage space and to saturate the fuel with nitrogen in ground storage facilities, e.g., in the trucks or central storage tanks (Ref. Section 2.c of the Tasking Statement). The process of saturating the fuel with nitrogen will be referred to as "fuel scrubbing" herein.

Concepts and design methodology for systems that accomplish the above referenced tasks have been developed. The concepts detailed in this Appendix E will describe the systems for: scrubbing the jet fuel of intrained O_2 while the fuel is in bulk storage tanks at the airport fuel storage facility; they will describe the mobile vehicle fleet that will be necessary to transport the fuel to the wing of the aircraft at airports where hydrant systems are not installed or where airplanes are parked in non-hydrant supplied remote locations; they will describe the production facilities necessary to generate NEA locally and the distribution system necessary to deliver NEA to the wing of the aircraft for Ullage Washing; they will briefly describe a patented system proposed to cool the fuel in order to provide an alternative to scrubbing and washing and; they will describe a patented system proposed to scrub the fuel with an alternate inert gas-CO_2.

This Appendix will also discuss issues associated with environmental concerns as it relates to fuel scrubbing and ullage washing as well as the effect of these processes on the performance properties of today's jet fuels.

Scoping Statement

- The Airport Facilities Task Team will investigate and develop design concepts covering the following areas associated with airplane fuel tank inerting:

- The installation, operation and maintenance requirements for an on-field inert gas generation, bulk fuel scrubbing with NEA and airplane fuel tank ullage washing system.

- System configurations to provide fuel scrubbing and ullage washing for various size airports and fuel handling (hydrant or mobile) processes.

- The physical impact on airport facility utility infrastructure resulting from the incorporation of an on-field NEA inerting system.

- The technical impediments, if any, associated with a suitable system design if the objective appears to be impractical or cost prohibitive.

- The economic impact associated with a viable method of delivering gaseous NEA and NEA saturated fuel into the wing of the airplane.

1.0 FUEL SCRUBBING AT THE TANK FARM

In order to prevent the O_2 inherently dissolved in the liquid fuel from coming out of solution and polluting the previously washed fuel tank ullage as the aircraft climbs, it may be required to scrub the fuel of O_2 before loading on the plane. The logical place to do this job is at the fuel farm where the fuel is inventoried and allowed to settle before being pumped into the hydrant system. However, because of the ability of Jet A-1 fuel to preferentially absorb O_2 from air, the entire purpose of the processing technology at the fuel farm needs to be removal of O_2 dissolved in the liquid fuel, preventing it from re-entering the fuel after treatment and dealing with environmental issues, such as VOC emissions, present at the tank

farm. Due to the more aggressive gas/fuel contacting that would occur if the fuel scrubbing technology were implemented, it is anticipated that VOC emissions would be higher than current levels, causing the need for the VOC abatement equipment. In addition to the processing technology at the farm, there is also a certain amount of LN_2 storage to back up the gas generation equipment to enhance reliability, as done at the concourse for ullage washing.

This fuel farm processing system is comprised of specialized gas generating and application equipment. The HIGH-PURITY GAS GENERATOR SKID (99.999% inerts) is used to strip the fuel of dissolved O_2 and to blanket the fuel storage tanks at the farm with N_2 to prevent re-entry of O_2 from air. The FUEL SCRUBBING UNIT, which is a gas/liquid fuel contacting system, uses the pure product gas from the HIGH PURITY GAS GENERATOR SKID to replace the O_2 in the fuel with N_2. TANK BLANKETING MANAGEMENT SYSTEMS control the pressure and O_2 concentration in the headspace above the fuel in the individual large storage tanks at the farm. Finally, emissions of fuel vapors from the fuel storage tanks, and vent gas from the FUEL SCRUBBING UNIT, will be controlled using an ENVIRONMENTAL ABATEMENT SYSTEM that employs liquid N_2 to cryo-condense the VOC vapors from the vent stream and return it to the fuel tanks. Essentially, all of these technologies work as separate unit operations at the fuel farm to ensure the delivery of fuel to the concourse that is scrubbed of oxygen.

To more easily understand the implementation of these various technologies to achieve fuel scrubbing, it is useful to consider the existing fuel tank farm at a typical airport. The simplest configuration is illustrated with three tanks in Figure 1-1 below. Liquid fuel from the pipeline continuously fills the tanks as the hydrant system is being supplied from them on a variable basis. The maximum flowrates for an airport the size of O'Hare can be filled and withdrawal rates in excess of 4,000 and 18,000 GPM, respectively. The cycle typically sees a piston of liquid fuel filling one tank as a similar flowrate of VOC laden air exits the vent to maintain constant pressure. Elsewhere, another tank is being drawn down, aspirating ambient air into the headspace to break any vacuum that is formed by the retreating liquid. The third tank rests for about 24 hours to settle out any liquid water that may be present in the system.

297925J2-050
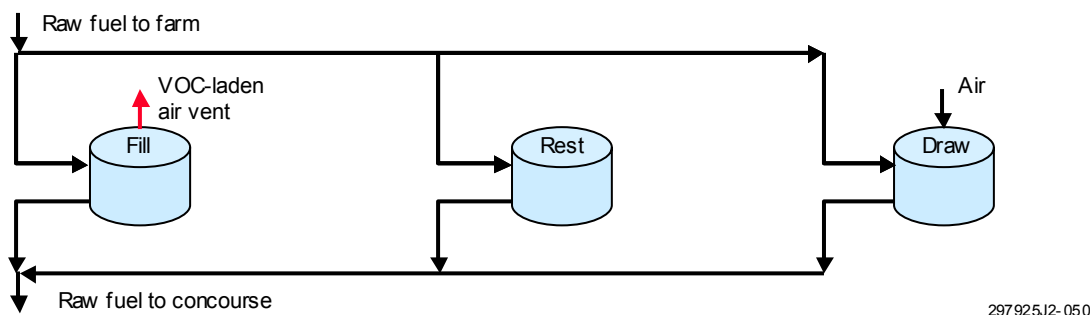
Figure 1-1. *Current Tank Farm Configuration*

The concept of fuel scrubbing is easily illustrated with some relatively minor additions to the current piping configuration at a fuel farm. This is shown in Figure 1-2 below, entitled Illustration of Fuel Farm Piping with Added Fuel Scrubbing Unit. With this new approach, raw fuel, containing 50 to 100 PPM of dissolved O_2, enters the FUEL SCRUBBING UNIT and is stripped of the O_2 via intimate contact with a stream of high purity N_2 gas. The N_2 replaces the O_2 dissolved in the liquid and dilutes the O_2 gas given off by the fuel. Approximately 2 volumes of N_2 gas are required for each volume of fuel processed. The end result is a fuel that is scrubbed of oxygen down to about 5 PPM. It has been estimated that the off-gas that exits the FUEL SCRUBBING UNIT unit contains about 1.5% O_2, as well as about 0.5% VOC vapors.
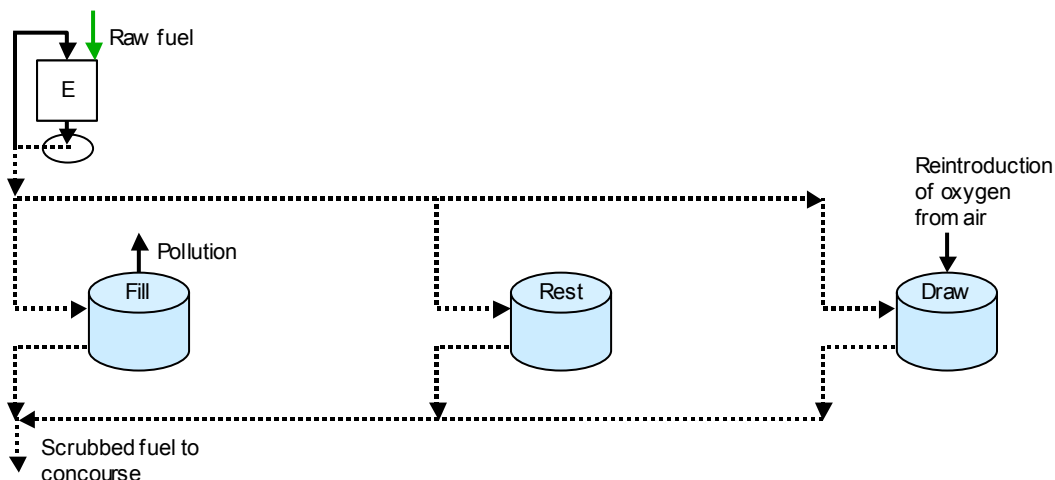
Figure 1-2. Illustration of Fuel Farm Piping with Added Fuel Scrubbing Unit

However, two issues still remain with this level of solution. The off gas that is displaced from the fuel tank being filled and the gas that is vented from the FUEL SCRUBBING UNIT, both of which contain some O_2 gas and fuel vapors, will pollute the air if not treated. In addition, O_2 in the air that would be aspirated into the fuel tank being drawn down, will ruin the fuel treatment job previously done by the FUEL SCRUBBING UNIT. Additional technology needs to be added to what is shown in Figure 1-2 to avoid these problems in order to meet all of the previously mentioned objectives for fuel scrubbing.

In the complete fuel scrubbing concept, as shown in Figure 1-3, the ENVIRONMENTAL ABATEMENT SYSTEM and TANK BLANKETING MANAGEMENT SYSTEM units have been integrated into the fuel farm to control pollution from VOC emissions and protect the re-oxygenation of the scrubbed fuel in the tanks.

The TANK BLANKETING MANAGEMENT SYSTEMS, mounted one per tank, automate the N_2 blanketing of the tank headspace by measuring and controlling the pressure and O_2 content of the gas above the fuel. The inlet valve is opened to introduce high-purity N_2 from the HIGH PURITY GAS GENERATOR SKID (not shown) to drive up the pressure and/or decrease the gaseous O_2 content. Similarly, if the pressure is too high, the vent valve is opened to exhaust some headspace gas into the low pressure gas header. Thus the tanks are continuously maintained at a given pressure and O_2 level, such as 8-inches W.C. and 1% O_2, respectively.
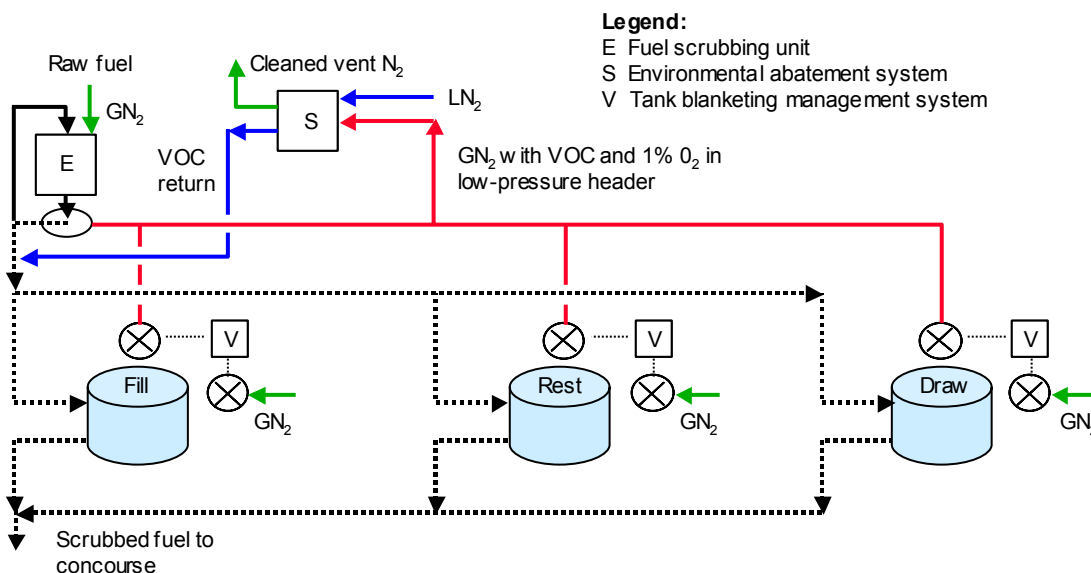
297925J2-052

Figure 1-3. Complete Aspect of Fuel Scrubbing Operation

A low-pressure header connects all of the vent valves on the fuel tanks and the gas vent from the FUEL SCRUBBING UNIT with the inlet of the ENVIRONMENTAL ABATEMENT SYSTEM. The fan on the ENVIRONMENTAL ABATEMENT SYSTEM will be used to control the back pressure within this low-pressure header. A target of about 5-inches W.C. has been selected for this header pressure which should be sufficiently low to easily exhaust gas from the fuel tanks and FUEL SCRUBBING UNIT.

The process gas flowing through the ENVIRONMENTAL ABATEMENT SYSTEM then contacts stages of increasingly cold heat exchangers to remove nearly 100% of the VOC's by condensation driven by LN_2. The liquid fuel is then sent back into the scrubbed fuel line that flows to the storage tank being filled. This is done so as not to deplete any compounds out of the normal JET A-1 mixture. The process gas, which has been stripped of fuel vapors, it then vented to the air, or possibly compressed and sent to the concourse for ullage washing, if a suitable pipeline is available. The spent N_2 gas, which was vaporized to cool the ENVIRONMENTAL ABATEMENT SYSTEM, is pure and will be sent to the high-purity N_2 header being fed by the HIGH PURITY GAS GENERATOR SKID.

1.1 FUEL SCRUBBING SYSTEM OPERATION AND MAINTENANCE

Maintenance requirements at an airport equipped with fuel scrubbing technology at the fuel farm would be moderate. The equipment is a bit more orientated towards chemical operations compared to the system for ullage washing. The endeavor would need a higher level of supervision with probably one employee overseeing the operation on a 24/7 basis. However, due to the reasonably passive nature of the heat transfer and gas generation systems, the maintenance & operating support for the farm would not be excessive. In most Air Liquide customer installations, equipment skids of the type used for fuel scrubbing typically run unattended.

Like the membrane skids, the HIGH PURITY GAS GENERATOR SKID would require the support typical for a large compressed air/filtration system. Oil and filter changes and bearing life issues on the compressors, filter drainage and carbon tower replacement for filtration and instrument calibration would require periodic attention. In addition, the LN_2 storage tank to supply the HIGH PURITY GAS GENERATOR SKID & ENVIRONMENTAL ABATEMENT SYSTEM would need refilling. The FUEL SCRUBBING UNIT is a passive gas/liquid contacting unit that would need little support except instrument cleaning & calibration. TANK BLANKETING MANAGEMENT SYSTEMS would need a semi-annual change of the oxygen cell, as well as typical instrument calibration. The

ENVIRONMENTAL ABATEMENT SYSTEM unit would require some mechanical support for the fan (lubrication, bearings, etc.), solenoid coil replacement, instrument calibration and liquid VOC pump service. It is anticipated that operation & maintenance duties would be handled by chemical technicians or engineers with a reasonably high skill level.

1.2 COST OF FUEL SCRUBBING APPLICATION AT O'HARE AIRPORT

The cost to implement fuel scrubbing for the eight fuel tanks currently at O'Hare Airport has been estimated in a proceeding section. The estimate includes the installed capital cost for the HIGH PURITY GAS GENERATOR SKID, FUEL SCRUBBING UNIT, ENVIRONMENTAL ABATEMENT SYSTEM and TANK BLANKETING MANAGEMENT SYSTEMS, along with interconnecting piping, foundations and electrical service upgrades. As with ullage washing, it is intended that Air Liquide would install and service the major equipment while the airport would be responsible for the piping and electrical to battery limits. Note that the cost of the HIGH PURITY GAS GENERATOR SKID and additional LN2 storage will be on a gas charge or leased basis.

A description of the components in the N2 based fuel scrubbing design is as follows:

- QTY(3) HIGH PURITY GAS GENERATOR SKID; 46,000 SCFH at 100 PSI & 99.99% N2 w/13,000 Gal LN2 Tank, Vaporizer and Buffer Tank(includes foundation & lights)

- QTY(2) 13,000 Gal LN2 Tanks for additional capacity

- QTY(1) 2000' of 150 PSI N2 piping,   6-inch, SCH 40 steel to FUEL SCRUBBING UNIT & Fuel Tanks.

- QTY(1) FUEL SCRUBBING UNIT to treat 4550 GPM of JET A-1; 1000 Gal Liquid/Gas Separator, PID control.

- QTY(2) Low Pressure Regulator for FUEL SCRUBBING UNIT off gas return to L.P. gas header; 1200 SCFM; 100 PSI in/1 PSI out.

- QTY(1) 2000" of 12" piping for Low Pressure Gas Header from FUEL SCRUBBING UNIT to Fuel Tanks; Sch 40, steel.

- QTY(8) TANK BLANKETING MANAGEMENT SYSTEMS for fuel tank; pressure & O2 control; incl. H.P. N2 B-fly valve.

- QTY(1) ENVIRONMENTAL ABATEMENT SYSTEM for recovery of VOC; 2400 SCFM Flow with 1% VOC; Incl. 2 parallel trains of multi-stage condensers; 98% VOC recovery.

- QTY(1) 200' of 2" super-insulated piping with 6" of Calcium Silicate jacket for LN2 to ENVIRONMENTAL ABATEMENT SYSTEM.

- QTY(1) TeleFLO Telemonitoring Package; 100 I/O w/RS-285 network & custom screen.

- QTY(1) Electrical service connection for Concourse, 2600Amps at 480 VAC, 3P

2.0 METHODS OF HOLDING "N$_2$ SCRUBBED" JET FUEL STORED IN THE REFUELING TANKERS

System Concept

Propose design/modification changes to "in-service" and newly manufactured aircraft refueling (tanker type) vehicles which will enable "scrubbed fuel" to be transported from airport storage to the wing of the aircraft.

Design Description

- During fueling, tanker inward venting is required to prevent collapse of the refueler tank

- Predominantly less than "tank full" delivery requires nitrogen to be supplied to the refueling tanker vents to prevent fuel contamination

- Tankers also utilize small "in-breathing" vents that thread into the manhole cover assemblies

- These vents automatically protect the tank from collapse during volumetric contraction of the stored fuel during decreases in ambient temperature

- Current design of typical vapor recovery system equipment does not provide for integration of these vents within the vapor recovery system

- All vents will need to be inter-connected within a system that will be feed by a N_2 supply. To accomplish this, modification of the tanker will be required

- Relocation of the in-breathing vents may require welding modification to the tank vessel. If so, these modifications would need to be completed at a facility certified to make such repairs

- After modification, tankers will mirror function of a "typical" vapor recovery system found on vehicle transporting flammable liquids on public highways

- These vehicles are required by the Code of Federal Regulations (40 CFR, Part 60) to be tested at the time of initial installation and then periodically thereafter to ensure vapor tightness

- It would seem advisable to require this testing/re-certification be mandated within the ruling

System Design Description

- Modifications include, relocation of in-breathing vent to a point that vapor recovery vent hoods and associated piping can connect all tank vents to common nitrogen supply

- psig N_2 pressure stream will be supplied to the vapor recovery system at all times

- The N_2 supply can be from stored gaseous or liquid nitrogen vessels mounted on each tanker vehicle

- Handling LN_2 will present a host of additional training and conversion issues, so gaseous nitrogen is presented for review in this report

- Our example is based upon the quantity of gaseous nitrogen required to fully displace the product dispensed from a 10,000 gallon capacity refueling tanker (approx. 1400 cu. ft.)

- If commercially available 300 cu. ft. high pressure gas cylinders were used, five tanks would be required mounted to the vehicle to accomplish one full fuel tank delivery

- Liquid nitrogen could be used, carried in a much small vessel (dewar) as it gases at a rate of 93 SCF per gallon. However vaporizers required to convert the liquid to gas with out freeze-up presents a spaces available problem on most existing units

- Given the volume of nitrogen required to hold tankers inert, it would appear a land-based connection to the tanker at the gate, using the same stream available for ullage washing the aircraft, is optimal

- 1 psig out-breathing vents will be installed in the nitrogen supply piping to vent excess pressure to atmosphere protecting the tanker against thermal expansion

- A pressure sensor in the nitrogen piping system will also be required. This sensor will shut-down the pumping operation to prevent collapse of the tank if a negative pressure (vacuum of 26 mbars) is sensed within the nitrogen supply system

- This safety system would be interconnected with the vehicle pumping system to close the tank internal valve, disengage the pump, or stop the engine based upon the original system design

- To provided a constant 1 psig nitrogen pressure to hold scrubbed fuel inert overnight or short-term storage will require much less nitrogen

- Again, for the purpose of this report, the 10,000 tanker referenced above will see a maximum volumetric shrinkage of approximately 200 gallons, based upon a 40°F change in ambient temperature

- 200 gallon reduction in fuel quantity x .1337 (conversion factor to CF) = 27 SCF of gaseous nitrogen required to prevent negative tank pressure in this extreme case

- Standard 300 cu. ft. high-pressure (2000 psig) nitrogen cylinder/s could hold a 10,000 gallon capacity refueler inert for a period of approximately ten days or longer

Impact on Current Airports

- To maintain a nitrogen blanket on top of scrubbed jet fuel, a land-based source of nitrogen will need to be provided to supply the tanker make-up venting during fuel delivery

- Proper sizing of the nitrogen supply system to be used for aircraft fuel tank ullage washing can provide a collateral benefit in this area

- When servicing remotely parked or operated aircraft where a land-based supply is not available, a mobile nitrogen dispensing vehicle will be required

- At a minimum, this will add to already congested ramp areas and will require additional personnel

- Typical infrastructure impact associated with additional personnel working within the existing facilities will apply

Safety Assessment

- Possible benefits associated with use of liquid nitrogen are out weighed by training issues associated with handling cryogenic liquids

- Addition of a mobile nitrogen supply vehicle in some locations (and as a back-up for land-based nitrogen delivery systems) will create additional congestion hazards

- Inerting tankers with nitrogen will pose additional risks associated with confined space entry of all tanks for inspection and cleaning

- All confined space (tank) entry procedures will need to be reviewed and amended to identify that the space is totally void of oxygen and cannot sustain life for any period of time

Environmental Evaluation (Identified)

- Modification of tanks to include vapor recovery type equipment along with blanket of nitrogen to prevent re-oxygenation of fuel may reduce VOC emissions at the airport

- This benefit will come if corresponding vapor recovery piping is present at the fuel farm to receive these vapors during re-loading of the tanker

Economic Evaluation

- Tanker modifications required will in most cases cause the vehicle to be taken to a certified tank welding/repair facility

- Estimated cost of modifications will range between approximately $3,800 for 3,000/5,000 gallon capacity refuelers to $6,800 per unit for larger capacity refuelers up to 17,500 gallons, excluding transportation

- Yearly pressure/vacuum testing (CFR 40, Part 60) will add re-occurring costs of approximate $600 per tanker for inspection.

- Other costs associated with manpower requirements are covered separately in other sections of the report

2.1 GAS SUPPLY

The airport facility team looked at the supply of three potential gases as possible candidates for fuel tank inerting – NEA (gaseous and liquid), CO_2, and Argon. Gaseous NEA was found to be the best candidate for use.

Gaseous N_2

Gaseous N_2 can be generated on site using ASMs. Systems can be sized for various types of operations, only requirement is electrical power. Redundancy can be obtained by use of liquid N_2 or additional compressors. Issues:

- Large Power requirements

- Need adequate real estate for installation.

- Systems will require high pressure for distribution. Aircraft fuel tanks have very low pressure restrictions. Accurate and reliable pressure control will be critical.

Liquid N_2

Liquid N_2 is primarily being considered for a backup to the fixed gaseous systems. It may have applications for mobile ullage washing for large transports. Issues:

- Cannot be produced on site.

- Cryogenic liquid will require special handling.

CO_2

There was concern about the ability of the gas industry to meet the estimated 1300 ton/day increase in demand that inerting and fuel scrubbing would create CO_2. The team contacted Barbara Heydorn, author of the SRI Chemical Economics Handbook on CO_2, to get a forecast on the impact this much increase in CO_2 demand for commercial aviation use would have. Barbara gave us the following comments:

- Given enough lead time, say 2-3 years, Industrial Gas companies would obtain capacity to meet the extra demand, BUT the market would be different than it is today. The new capacity would come from lower purity feedstreams or from sources that are farther away from demand centers. Lower purity feed streams mean higher costs to purify and therefore higher FOB prices. Sources further from demand centers mean higher distribution costs therefore higher prices.

- Volatility in supply and pricing could be a problem for commercial aviation use. CO_2 is usually a byproduct of a chemical process. Many of those processes are susceptible to natural gas prices. For example, with the current high price for natural gas, many ammonia producers are not operating. All the CO_2 that was usually available from ammonia producers dried up.

- Three areas that do not currently have enough supply appear to be where commercial aviation demand could be the highest -- the Northeast US (La Guardia, Newark, JFK, Boston), Florida (Miami, Orlando, Tampa) and Southern California (Los Angeles). In the past 5 years there have been many allocations and interruptions in supply to those areas.

Argon

Argon was suggested as an alternative to NEA. The theory was that due to argon's higher molecular weight, it would perform better in cross-vented tanks. The team was unable to find any evidence to support this. Since argon is not as readily available as NEA and the cost was estimated to be ten times as much as NEA, argon was not pursued further.

3.0 FUEL COOLING

This concept was insufficiently developed to allow the AFT to fully evaluate it and develop the economics of the proposed concept. Also, since this is basically a form of fuel scrubbing, a means to inert the CWT would be required.

System Description

The fuel-cooling concept consists of both refrigerating fuel and/or washing the airplane fuel tank ullages with inert gas. The two separate processes may be used separately or combined. The cooling systems supply fuel to the airplane at less than 40 degrees F. Cooling facilities (located away from congestion) cool the entire airport fuel supply (hydrant and/or truck) to less than 40 degrees F. Inerting gas for ullage washing is stored (located away from congestion) and transported to the airplane on gas service vehicles in a cryogenic phase and converted to a gaseous phase as needed for ullage washing.

Impact on the Airport

Fuel cooling installations are designed to result in a minimal addition to airport gate congestion as all fixed cooling facilities are installed at or in the vicinity the fuel farm which is away from the gate areas. As the entire airport fuel supply will be cooled to a lesser temperature, to meet the massive peak flow demands caused by banks of airplane arrivals, thermal energy will be manufactured and stored in thermal banks or ice tanks. The stored cold energy will be applied to the fuel supply en masse. Large airport facilities will be of substantial size and require full time staffing. In locations where space at the fuel farm is limited, cooling systems can be located off the airport and cold energy brought to the fuel farm hydrant via pipeline. Hydrant modification involves installation of in-line heat exchangers at or near the fuel farm. Power demand will be substantial and likely exceed available power supplies at or near the fuel farm.

Pros and Cons

1. Small & Medium Airport

   Small and medium size airports can obtain self-contained, semi-permanent, packaged cooling and gassing units avoiding the complexities of nitrogen manufacturing equipment.

2. Empty tanks

   Under these circumstances, ullage washing with an inert gas is relied upon until flight conditions naturally make the tank non-flammable.

3. More than just the CWT

   The cooled fuel concept and inerting gas injection extends the flammability reductions into all tanks, not only the CWT.

Environmental Impact

1. Airplane vented VOC emissions and their contribution to air pollution must be studied further.

2. Static charging of the fuel and its effect must be studied further.

3. The effect of precipitating water from solution during cooling and its effect upon filtration equipment must be studied further. The effect of precipitating water from solution during cooling and its effect upon airplane flight performance must be studied further.

4.0 CO$_2$ FUEL SATURATION

This concept was insufficiently developed to allow the AFT to fully evaluate it and develop the economics of proposed concept. Before a full evaluation can be done more study will be required. Areas that will need more work are details of the actual components that would be required by the ground portion of the system, modifications required by the fueling vehicles to maintain the CO$_2$ in solution, the aircraft modifications that would be necessary, and a further study of the availability of CO$_2$.

Issues have also been raised regarding the possible impacts on pump cavitation and possible corrosion due to the possible formation of carbonic acid in the presence of water. These would have to be resolved before this can be pursued further. Also since this is basically a form of fuel scrubbing, a means of inerting the empty CWT would be required.

4.1 SYSTEM DESIGN CONCEPT

The system consists of a CO$_2$ (commercially available gas) and jet fuel mixing apparatus, which preloads the jet fuel with CO2. In one variation of the Airport Facility System, the CO$_2$ is derived from a liquefied CO$_2$ storage tank, converted to CO$_2$ gas and mixed in the Jet-A in a gas absorber tower (at an optimum gas-to-fuel ratio). Thereafter the CO$_2$-enriched fuel is stored in a fuel shipping tank having a floating pan (the combination tank and pan maintain the desired gas-to-fuel ratio of the treated fuel). The CO$_2$-enriched fuel is then transferred as needed from the shipping tank to all aircraft re-fueling sites using the existing fuel pipeline and hydrant systems (for hub airports) or the existing truck delivery system (at non-hub airports).

4.2 ENVIRONMENTAL EVALUATION (KNOWN ISSUES)

As an environmental benefit there may be reductions in engine exhaust soot particulate due to the mixing of >0.1 volumes of CO$_2$ in kerosene-based fuels. For example in EPA Test Data soot reductions in the range of 20-25% are seen with concentrations of 20-45% CO$_2$ in Diesel #2 (a close cousin to jet fuel). Soot reductions up to 60% were recorded in a variety of other calibrated emissions tests performed on Diesel fuel at different independent test facilities. It is not known if similar effects would be obtained in aircraft operations. Depending on the method that would be required to scrub the fuel with CO$_2$, an increase in VOC emissions similar to those found with NEA scrubbing could be possible.

4.3 ISSUES

Two of the major issues that have been identified are covered below. The solutions offered are those of the system developer and have not be evaluated by the AFT for effectiveness or cost. More research would be needed.

4.3.1 Cavitation

Absorbed air concentrations in Jet Fuel are known to reach gas-to-fuel ratios as high as 15% in Jet Fuel, which to date have not produced fuel pump cavitation problems. Nonetheless, the literature indicates that the presence of bubbles facilitates cavitation (NOTE: CO$_2$-enriched fuel is comprised of CO$_2$ *micro-bubbles*). Although the concentrations of CO$_2$ in the proposed CO$_2$-enriched fuel might be expected to exceed 15%, experimentation with boost pumps is needed to determine 1.) if cavitation will in fact, be an issue, and if so, 2.) what is the lowest gas concentration of *micro-bubbles* that causes cavitation?

There are two basic solutions to reducing inert gas in fuel before the gas-enriched fuel reaches a boost pump: 1) the use of a centrifugal pump prior to the boost pump to separate gas from the fuel, 2) the use of high-area contactors that have a medium not wet by the fuel but that does attract gas bubbles (this system can be made with no moving parts and with no power source). Both approaches are being examined by the developer of the system.

4.3.2 Corrosion

There was concern about corrosion on aluminum surfaces in fuel tanks. Corrosion is caused by the presence of carbonic acid. Carbonic acid is formed when enough CO_2 contacts free water. When very high concentrations of CO_2 were tested in fuel, a very small amount of fuel was converted to organic acids, but there was no detectable change in the energy content of the fuel. The carbonic acid Aircraft fuel tanks are equipped with and regularly employ water-scavenging means. Hydrant and Refueler truck fuel systems also remove water from fuel before it is pumped aboard an aircraft. Other water drying approaches may also be a possibility.

5.0 ULLAGE WASHING

Washing the ullage of O_2 gas in an airplane fuel tank has been proposed in order to eliminate, or greatly reduce, the ability of an ignition source in the tank from causing constant-volume combustion of the fuel vapors present. Simply stated, fuel vapors cannot burn unless a sufficient amount of oxygen is available to support and propagate the combustion. The ullage in the airplane fuel tank is washed with a lower NEA, 97% to 98% purity, to remove a large portion of the O_2 gas from the air that is initially present in the ullage. The 97 to 98% NEA stream is produced using a membrane gas generator skid.

The 97 to 98% NEA purity was chosen to be the most cost effective inerting agent, as it is less expensive than higher purity gas but contains half the O_2 content of a 95% inert product. The volume of gas for the inerting duty has been chosen by the Ground Based Design Team to be 1.7 times the volume of the airplane tank to be washed, based on an empty tank. Under these conditions of inerting agent purity and volume, tests have shown those O_2 levels of less than 9% will be produced within the ullage space of an empty fuel tank. Therefore, no O_2 meter for gas analysis will be needed to verify ullage washing, which helps to minimize complexity. More importantly, with tanks that are even partially full of fuel, the O_2 content is expected to be reduced to even lower than the 9% level, due to the larger number of actual volumes of NEA flowing through the system.

NEA is generated continuously, from air, using membrane gas separation technology. Essentially, air is compressed, filtered of solid particles and liquid aerosols and fed to bundles of hollow fiber polymeric membranes where the CO_2, O_2 and water vapor is removed from the N_2 stream. These gaseous impurities are vented at low pressure while the high-pressure enriched N_2 product, at 97 to 98% purity, exits the skid, via a surge tank. Backed up with a storage vessel of liquid N_2 (LN_2) and a vaporizer a continuous seamlessly transfer of NEA through the gas supply lines will be assured. It is envisioned that one large membrane gas generator skid and back up LN_2 tank would be supplied per airport concourse, mainly to minimize the need for long piping runs between terminals. The NEA would then flow through a header, which would be located along the roof of each concourse, at a pressure of about 150 PSIG. The header is anticipated to be constructed of 2-inch diameter, Type K copper tubing. This header would feed an array of metering stations, located one per gate, to supply gas to the airplanes for ullage washing under controlled flow and pressure conditions. A diagram of the membrane gas generator skid at a given concourse is shown below in figure 5-1.
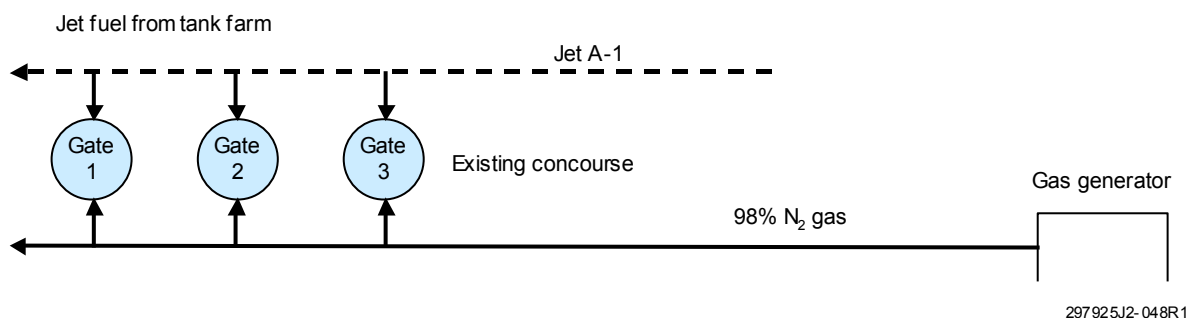

Figure 5-1. Membrane Gas Generator at Concourse for Ullage Washing

At multiple concourse airports it would be prudent to consider the inter-connection of membrane skids between terminals, with a larger manifold. While the capital cost to achieve this would not be insignificant, the benefit would be an additional level of redundancy, without LN_2 backup if one skid were down for extended maintenance.

The metering stations, for injecting NEA gas under flow & pressure controlled conditions at each terminal gate, are shown pictorially in Figure 5-2. The station is connected to the concourse NEA header on one end, and to a specially designed connector on the airplane at the other end. The function of this system is to reduce the O_2 content in the ullage space on the airplane by supplying a given amount of low pressure NEA to the ullage from a high-pressure source. A solenoid valve and a pressure regulator are used to initiate and complete a period of constant gas flow rate to the airplane. By maintaining this constant flow for a time appropriate for a given airplane, NEA is then injected into the ullage. The gas is made available by the regulator at a pressure of only a few pounds per square inch gauge (PSIG). In case of maintenance needs, the shut off valve would be used to block off the station. The hose reel allows for connection from the station typically located at the end of the jet-bridge, to the airplane.
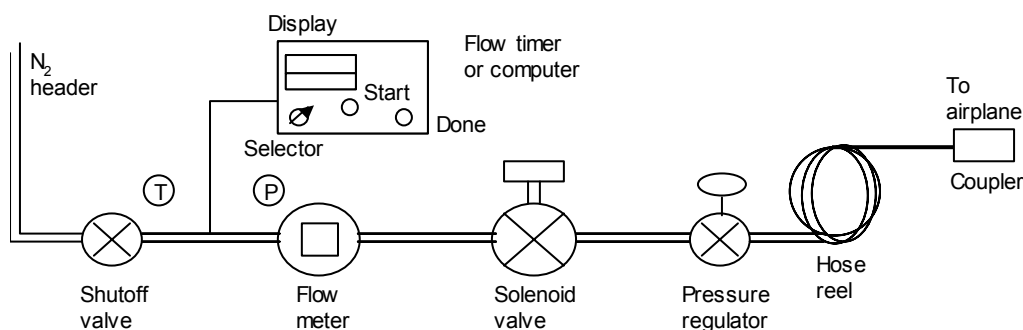
Figure 5-2. Typical Metering Station NEA Flow and Pressure Control

The heart of the gas metering station is the flow meter, flow control terminal and flow valve. The flow control terminal comprises a lockable weather- proof housing that contains a flow computer and delivery receipt printer. The gas metering station would be designed to operate in an unheated, outdoor service environment (temperature, moisture and vibration) under applicable electrical safety classifications. As previously described, the flow meter and flow computer delivers a pre-set quantity of NEA to the aircraft's tank ullage. The delivery of this gas to the ullage is measured with reference to standard conditions (i.e. 60^OF and 1 atmosphere). Hence, the required pre-set amount of gas is delivered regardless of the ambient temperature or source gas pressure.

The flow computer is essentially a device to allow gas to flow to the airplane ullage for a given amount of time, and then to display the actual volume of gas injected. The flow computer would include a selector to choose the type of airplane being inerted, a start button to control the solenoid valve, an indicator light to show when the job is done and a dual display to illustrate required and injected gas volumes. In addition, the unit could be configured so that the operator is required to perform a security check (e.g., input an authorization code) to initially access the system. Stored within the flow computer would be the appropriate inerting times which will, at a given constant gas flow rate, produce an inert ullage space above the fuel (or in the event of an empty tank – complete tank contents) in the airplane tank.

As an example, if an operator is required to inert a 737, he would connect the coupler to the plane, select the appropriate volume on the selector and verify the correct pressure value on the flow control display. The upper display on the flow computer would show the volume required for ullage washing of a 737 aircraft, say 1360 SCF. The operator would then depress the Start button. A NEA flow of 100 SCFM would occur for 13.6 minutes to produce the recommended volume of NEA for the 737 in this example. Then the indicator light would illuminate (indicating the task is done) and the solenoid valve shut. The

lower display would read 1360 SCF based upon a total of the cumulative gas flow through the metering system, at standard conditions. If the value were low, an option would exist for the operator to adjust for more NEA into the ullage to satisfy the requirement. He could either verbally inform the crew that the plane has been inerted, or a written receipt could be printed to do the same. Delivery of this data could also be sent via a suitable communications link to a central computer, if required.

It became obvious that ullage washing systems will have to be customized for each airport. However, the major components required for design of a fixed, ground based ullage washing system for various classifications (sizes) of airports may be found in the generic layouts presented in Appendix E.

5.1 ASSUMPTIONS
- During the study assumptions had to be made by the Working Group and the AFT. The following are the assumptions that the AFT used in developing the design concepts for the ullage washing systems.

- The process was not to affect the airplane turn time. This was a goal agreed upon by the Working Group.

- Other studies have assumed that the inerting would be done after fueling. While this would reduce the amount of start when the airplane arrived at the gate (i.e., empty tanks). This was according NEA required, it would have possibly increased the aircraft turn times

- Only the CWT would be inerted.

- 800 SCF was used as the average gas requirement. This is the volume of the small generic airplane model used in the study.

- 1.7 times ullage volume would be required to perform the task. Testing that had been done showed various ranges of volume to accomplish the inerting. The team settled on this figure. It may be possible in actual operation the amount of NEA required could be more or less.

- Fixed system sized for a utilization of 0 to 2.4 times the average to handle peak operations. At large hub airports the aircraft arrive in banks. This creates a high demand over a very short period of time. The systems will need to be able to recover between banks. The amount of real estate available may also limit the size of the backup storage.

- A maximum of 15 min to inert a small airplane. This was based on the average turn times supplied by the Maintenance and Operations team.

- Large and medium airports would use fixed equipment as the primary means for gas supply, and small airports would use mobile equipment. The team felt this would be the most practical approach.

5.2 MOBILE ULLAGE WASHING DESCRIPTION
Where it is not practical to supply a land-based source of nitrogen to ullage wash airplane fuel tanks at the loading gate, remote-mobile nitrogen dispensing equipment will be required. This equipment can be either mobile nitrogen generating equipment, or LN_2 tankers, with vaporizers to convert the liquid to a gas.

Two factors have influenced selection of nitrogen generating equipment over LN_2 and vaporizing equipment for presentation in this report:

- Training and related safety issues associated with handling cryogenic liquids

- Cost of ongoing purchase of LN2 as compared with costs of generation of gaseous N2 directly from the air using compressors and high purity nitrogen membranes

Design of mobile ullage washing vehicles will emphasize ease of operation, by allowing operators to select predetermined automatic cycle times specific to each aircraft type. Vehicles will be designed with a

high volume output screw-type compressor, appropriate filter, high purity nitrogen separators, specially designed meter, pressurized nitrogen storage tanks and related automated control system. A vehicle brake interlock system is required to ensure delivery hoses/nozzles are properly stowed, prior to release of the vehicle brakes.

The overall size of mobile NEA generating equipment could become an issue due to the quantity of high purity membranes required. When consideration is given to ullage washing large transport category aircraft center fuel tanks, as well as possibly providing "make-up" nitrogen to hold refueling tankers inert, size clearly becomes an issue.

Current ramp congestion dictates mobile "ullage washing" vehicles utilize the smallest package/footprint possible to accomplish the task.

It is estimated that to service remotely parked or operated aircraft, especially freighters, and as back-up for land-based system, mobile ullage washing vehicles will typically number from 65-85% of the number of refueling tankers operating at a particular airport. The addition of mobile inerting processes at the terminal gate is certain to exacerbate complications associated with congestion around the aircraft. There are a number of existing services associated with airport ground operations including fueling, baggage handling, food, and cleaning services among others. All operations require vehicles to travel to and from the aircraft in a very short period of time. There exists an increased risk of accidents during operations attributable to the inerting process. The addition of the inerting process could decrease the available time to conduct all other ground operations, further adding to the risk.

At small airports or at foreign airports with a U.S. only implementation, it may be more cost effective to have all mobile equipment when compared to fixed infrastructure costs.

All problems generally associated with a significant increase in personnel staffing while operating within the same physical area will be present.

Small to medium size transport aircraft mobile inerting vehicle:

- Where remote ullage washing for medium size transport aircraft and smaller is required, a mobile nitrogen-generating vehicle can be provided in a very user-friendly package.

- This vehicle would also utilize a high-flow rate air compressor to supply large volumes (270 CFM) of air to a high purity nitrogen membrane separation system.

- However, the smaller demand for air pressure will allow the compressor to be powered by the chassis power-plant/drive-line via a transfer case.

- A unit of this type could typically manufacturer 97% pure gaseous nitrogen at a rate of 6,500 CFH while only having a footprint comparable to that of a typical hydrant system dispenser (approximately 20' OAL x 8' OAW x 9' OAH).

Large transport aircraft inerting vehicle -using liquid nitrogen vaporizer:

- Another consideration for mobile ullage washing of larger transport which could easily be used for all aircraft size categories is conversion of liquid nitrogen

- Liquid nitrogen converts at a rate one gallon of liquid nitrogen to 93.1 CF of gaseous N2

- Equipment size is dictated by providing adequate vaporizing units to prevent freezing up.

- For this study, a concept vehicle having a 400-gallon LN2 storage tank and adequate vaporizers to convert 193 gallon into 18,000 CF of gas within a 20 minute period are used.

6.0 ENVIRONMENTAL ISSUES FOR FUEL SCRUBBING SYSTEM CONCEPT

General environmental issues are addressed as part of this document to identify basic direct and indirect environmental impacts with the fuel-scrubbing concept discussed within this section of the overall report. The impacts fall into the following categories:

- VOC emissions

- The airport environment

- Other environmental issues

Values and quantities of undesirable materials and impacts are not quantified in this section of the report. Instead, the impacts are identified as they generally relate to existing airport and airline environmental initiatives. Quantification of these impacts is deferred until a more thorough and complete analysis can be completed (presumably after a specific SYSTEM CONCEPT is selected for further development.) Other than the VOC emissions, which could be mitigated by a costly vapor recovery system, the environmental impact resulting from the implementation of fuel scrubbing is assumed to be relatively minor.

Environmental protection infrastructure must be added to each airport fuel storage facility. The systems and equipment include pumps and other electric motor driven equipment, aboveground liquid nitrogen storage tanks, gas tanks and piping.

VOC Emissions

- Installation of vapor recovery system. Data from a simple experiment from two different sources indicate that substantial amount of light hydrocarbon molecules would be stripped from the fuel during the scrubbing process. A vapor recovery system would be an essential component of this system to mitigate this adverse impact on the environment.

- All refueler trucks, that serve aircraft parked in remote or in the cargo areas or at an airport where there is no hydrant system, have to be modified. A nitrogen generating unit added to the rear of the vehicle will maintain an inert atmosphere in the tank head space and maintain a slight positive pressure in the tank by replenishing with nitrogen while the tank fuel level is being drawn down during aircraft refueling. During the refilling cycle of the refueler a means of capturing vented emissions would have to be developed. These modifications may result in an increase in VOC emissions from this intermediate mobile fuel storage.

Airport Environment

- Truck traffic to deliver liquid nitrogen to the tank farm area results in additional use of fossil fuels.

- The increase in the number of Ground Service Equipment (GSE) vehicles mandated by this system will add to the emissions from the internal combustion engines that power them.

Other Environmental Considerations

- Environmental remediation of land. Any building activities atop the airport tank farm site will require that existing environmental remediation methods be altered and/or that remediation be undertaken prior to the construction of any supporting infrastructure.

- Indirect impacts include items such as negatively influencing airport, city and regional air quality.

Summary

- No positive environmental impacts (improvements to the environment) were identified for any of the concepts in this report.

- No data are available on the soil condition of any given site nor is quantified air emission data available to establish an emission baseline. A baseline would be useful in measuring incremental impacts to the environment.

6.1. POTENTIAL IMPACT ON FUEL PERFORMANCE FROM ULLAGE WASHING AND FUEL SCRUBBING

The Federal Register of July 14, 2000 (Vol. 65, No. 136, pgs. 43800-43802) announced the formation of a new Aviation Rulemaking Advisory Committee (ARAC) with a "Tasking Statement" covering the formation of an Aircraft Fuel Tank Inerting Harmonization Working Group.

The tasking statement requested that the ARAC provide, among other tasks, methods of introducing nitrogen gas into the affected fuel tanks to displace the oxygen in the ullage space and to saturate the fuel with nitrogen in ground storage facilities, e.g., in the trucks or central storage tanks. The process of saturating the fuel with nitrogen will be referred to as "fuel scrubbing" herein.

A concept and design methodology for a system that proposes to accomplish the above referenced tasks has been developed. However, during the conceptual deliberations as to how an effective system might be designed, manufactured, installed and made operational, concern arose with respect to the effects ullage washing and fuel scrubbing may have on the performance characteristics of aviation turbine fuel. In addition, there were concerns expressed about the environmental impact resulting from the inerting process, especially as a consequence of fuel scrubbing which involves vigorously mixing nitrogen gas with a high flow fuel stream.

This report subsection is intended to summarize the concerns, the findings of preliminary laboratory analysis performed by two oil company task team members, and recommendations for further study of the fuel tank inerting scenario.

6.1.1 Concerns

Concerns were raised that ullage washing and fuel scrubbing would degrade certain performance properties of jet fuel by driving of the "light weight molecular ends" of the fuel. The "light ends" influence several specification properties of jet fuel including distillation, flash point and freezing point. Another concern expressed was the uncertainty of how these processes might impact the re-light-at-altitude characteristics of the fuel. Questions were also raised regarding the performance of additive packages, e.g., anti-oxidants, anti-static additive, added to the fuel to enhance or modify particular characteristics of the fuel.

In order to obtain a broader perspective on these questions and other issues, a notice was circulated via the ASTM committee charged with Aviation Turbine Fuel specification (ASTM D-1655) maintenance asking all U. S. and non-U. S. Refineries, engine, airframe and component manufacturers to provide feedback and/or information they may have on the performance characteristics of fuel subjected to ullage washing and/or scrubbing. Because these inerting concepts were new to many of the responders, more questions were raised than answers received. The additional concerns expressed ranged from complete engine re-certification may be required, to the other extreme where it was believed nitrogen inerting would improve at least the fuel stability characteristics and therefore would be a benefit.

The last area of concern that arose during discussions of the fuel inerting concept was that involving environmental considerations. Again, flowing nitrogen gas over a partially filled fuel tank and/or the vigorous mixing of nitrogen gas with fuel during the scrubbing process would, according to general opinion, result in significant volatile organic compound (VOC) release to the atmosphere at the airports' fuel storage depot. These VOCs would aggravate the already thorny issue of air pollution on and around today's airports. Feedback and factual data was requested from stakeholders, including the U. S. Environmental Protection Agency (EPA). Again, more questions than answers came from this inquiry.

6.1.2 Preliminary Laboratory Analysis

AirBP and Texaco performed elementary experiments on ullage washing and fuel scrubbing using nitrogen and carbon dioxide gases (final reports are addenda to this section).

Preliminary results of these experiments indicate that ullage washing and fuel scrubbing with nitrogen gas has little affect on the conventional properties of jet fuel. However, a measurable change in vapor pressure occurred from fuel scrubbing and the CO_2 scrubbed fuel exhibited an increase in acid number. Significant quantities of VOCs were released during both processes regardless of the inert gas used. The VOC release may lead to serious health and safety issues that must be addressed.

First, the physical properties change; in one experiment it was shown that there is an increase in the fuel's vapor pressure after the scrubbing process. This vapor pressure increase phenomenon is not totally understood at this time; however, it does suggest that there may be a deleterious effect in controlling the flammability of the aircraft fuel tank headspace atmosphere. The increase in vapor pressure may affect the performance of the different fuel pumping devices used on today's aircraft.

There was also a decrease in the fuel's electrical conductivity, which will require further investigation. Changes in this fuel property will require a full understanding of the phenomenon because of fuel handling safety and additive performance issues.

A significant release (addressed further in this summary) of VOCs occurred during the ullage washing and scrubbing processes which obviously changes the bulk fuel composition. The removal and recombining of the VOC condensate, after a vapor recovery process, will require additional study to ensure that there is no deleterious effect on engine performance due to a reconstituted fuel blend. Although no statistical difference was measured in the fuel's distillation characteristics, flash point or freezing point, a more thorough analysis of these properties should be performed to verify the preliminary findings. Additionally, because the loss of these light-ends may effect altitude re-light, a thorough analysis of this characteristic should also be carried out, unfortunately this analysis could not be done in the time allotted to this project.

The experiments conducted using CO_2 as the scrubbing gas (CO_2 injection was one of the inerting processes considered during the team's discussions, but time did not allow for a complete conceptualization of this technique) showed a much greater effect on vapor pressure than N_2 and also caused the Acid Number of the bulk fuel to increase. This finding was not totally unexpected because prior experience has shown that with water laden (including dissolved water) mixtures and subsequent CO_2 saturation, carbonic acid may form as a by-product of this chemistry. Obviously the formation of any compound that may enhance or accelerate corrosion of the aircraft fuel tanks is not a desirable attribute of a fuel.

Second, the industrial health and safety issues; the experiments indicated that the carcinogen Benzene may be concentrated in the vapor phase at concentrations that could exceed the 0.1% (wt) limit established for regulating a material as toxic. Obviously, this matter is of the greatest concern with regard to employee health and the environment surrounding the airports' bulk storage depot and will have to be addressed.

An additional employee and facility safety problem is also introduced when fuel is exposed to the scrubbing process and this is the extremely flammable vapor atmosphere created by the light-end VOC emissions. Very careful attention will have to be taken in the design of any mechanical equipment used to recover and dispose of these VOCs.

Ullage washing will result in the release of a low oxygen, high inert gas concentration mixture (N_2 or CO_2) from the center wing tank vents. Persons working in and around this area may be exposed to air with an oxygen level below that which is required to sustain normal respiration. The hazard level will increase as the number of aircraft in a localized area undergoing the inerting process increase. This asphyxiation hazard must be studied in more depth before any large-scale inerting is implemented.

<u>Third, the environmental impact issues</u>; the ullage washing and fuel scrubbing processes have been shown to release a significant amount of VOCs. These VOC releases were measured in the 1%+ (volume) range during the experiments. To put this volume number in perspective it represents a release of an equivalent volume of 21,000+ gallons of jet fuel from a typical 50,000-barrel (2.1m gal.) storage tank found at many airports. This release would be expected to occur each time a fuel receipt of this size is received into storage and subsequently processed through the scrubbing cycle. The environmental, as well as the economic, impact of releases of this magnitude will require careful design and operation of costly vapor recovery systems near the bulk storage facilities. As more regulatory pressure is exerted on today's management and operators to "clean up the air" on and around the airport, release of additional pollutants, caused by some new process, becomes unacceptable regardless of the perceived benefits.

The EPA representative queried during the "get-some-feedback" process succinctly put future work on this issue into perspective by recommending a "1) literature search for theoretical and experimental analysis of the effects of fuel tank inerting or similar fuel treatments on engine exhaust emissions, 2) explicit discussion, involving appropriate experts of this concern in FAA rulemaking activities relating to fuel tank inerting; and 3) experimental research to validate expectations regarding impacts of inerting methods on engine exhaust emissions."

6.1.3 Future Work
As the foregoing indicates there are a number of issues that need to be addressed, better understood, and solutions found before ullage washing and/or fuel scrubbing is implemented on a large scale. The following is only a short list of the issues that come to mind:

- The characteristics of scrubbed fuel performance in today's turbine engines need further investigation.

- The impact of ullage washing and fuel scrubbing on employee health and safety will have to be better understood so appropriate action can be taken.

The impact of ullage washing and fuel scrubbing on the environment will have to undergo an extensive review. There was not enough time or readily available information during this ARAC project to become fully knowledgeable on the subject and propose concept designs around the impediments identified.

7.0 LABORATORY REPORTS

ADDENDUM 1:
AIR BP LABORATORY REPORT
<u>Nitrogen/Carbon Dioxide Inerting of Jet Fuel Tanks</u>

7.1 SUMMARY
A limited study to evaluate the impact of ullage washing and fuel scrubbing using carbon dioxide and nitrogen on the properties of jet fuel has been performed. Displaced vapor was found to contain up to 18 mg/liter light hydrocarbons, which on condensation would give a volatile, highly flammable liquid similar to gasoline. The liquid jet fuel remained largely unchanged after exposure to nitrogen, however, exposure to carbon dioxide resulted in a significant increase in vapor pressure (+16.7 kPa) and acidity ($\geq$+0.041 mgKOH/g).

7.2 BACKGROUND
Air BP performed a study to examine the use of nitrogen and carbon dioxide gases to inert jet aircraft fuel tanks and remove dissolved oxygen from the fuel. This study examined fuel quality before and after nitrogen/carbon dioxide has been introduced, and the composition of the vapor above the fuel.
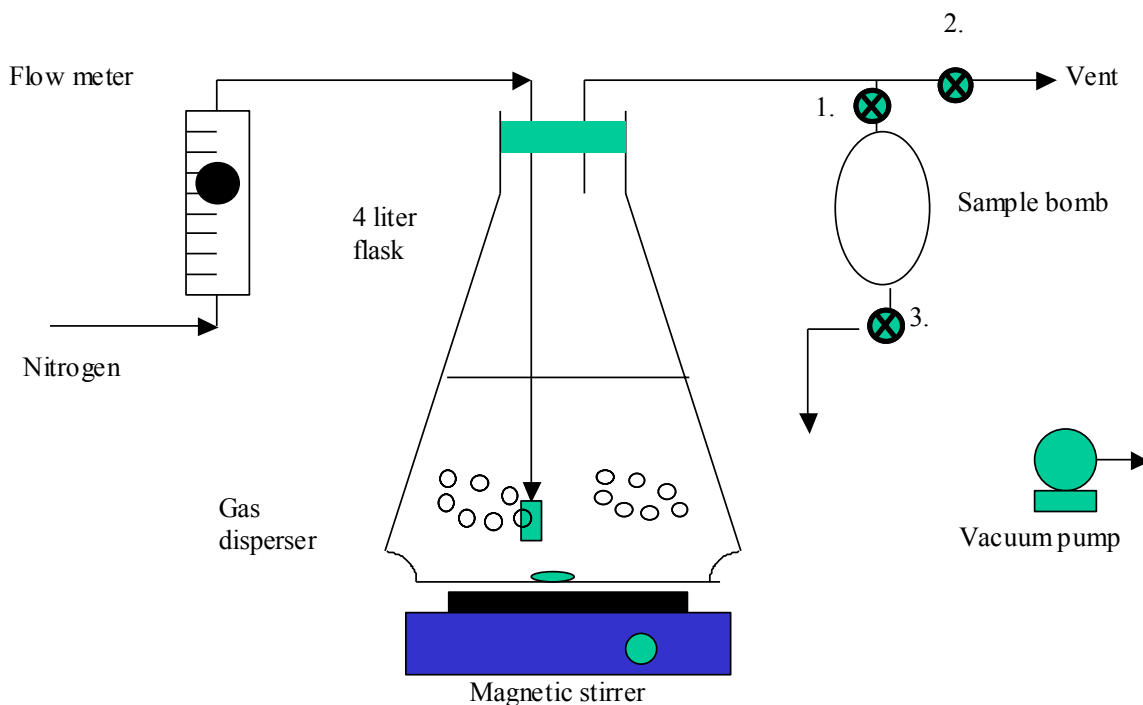
Figure 7-1.

7.3 APPARATUS
Figure 7-1 provides a schematic diagram of the apparatus.

7.4 METHOD
1. Three liters of commercial jet fuel, reference number W01/067, was introduced into the 4-liter sample flask.

2. The temperature of the fuel was recorded.

3. Valves 1 and 2 were set such that nitrogen would flow via valve 2 to vent.

4. Nitrogen was introduced into the fuel at a steady flow rate of 380 ml/min.

5. The sample vessel was evacuated and connected to the line.

6. Valve 1 was opened to draw vapor into the sample vessel.

7. Valve 2 was then shut while simultaneously opening valve 3 such that all vapor flowing from the flask would pass through the sample vessel.

8. After a period of 20 minutes, the sample vessel was sealed while simultaneously opening valve 2.

9. Steps 3.5 to 3.8 were repeated to give a second sample 40 minutes after the start of the experiment. Both samples were then analysed by gas chromatography.

10. The liquid fuel was transferred from the sample flask to an epoxy lined can, air displaced from the headspace with nitrogen, sealed and analysed.

11. Steps 3.1 to 3.10 were repeated with a fresh sample of jet but the nitrogen flowing into the flask was set to only pass over, rather than through, the liquid.

12. Steps 3.1 to 3.11 were repeated with a fresh sample of fuel but the nitrogen was replaced with carbon dioxide.

7.5 RESULTS AND DISCUSSION
Vapor Phase

Vapor phase analysis for the nitrogen and carbon dioxide studies are provided in Tables 7-1 and 7-2 respectively. The hydrocarbon concentration in the vapor phase showed some time dependence, particularly for the nitrogen sparge through liquid fuel which increased from 8.1 mg/liter at 20 minutes to 17.8 mg/liter at 40 minutes. This was significantly higher than other results obtained and may warrant further investigation. In general, gas sparge over, rather than through the fuel gave slightly lower concentrations of hydrocarbon in the vapor. The chemical species present were indicative of light hydrocarbons left entrained in the fuel during manufacture. Condensation and recovery of such hydrocarbons would give a product similar in hazard to motor gasoline, i.e. high vapor pressure, low flash point and requiring carcinogenic labelling due to the presence of benzene.

Liquid Phase

Liquid phase analysis, featuring standard jet fuel inspection data, for nitrogen and carbon dioxide studies after 40 minutes gas sparge, are provided in Tables 7-3 and 7-4. Nitrogen sparge had very little effect, if any, on the properties of the jet fuel. However, carbon dioxide gave a significant increase in fuel acidity, $\geq$+0.041 mgKOH/g above base fuel level. This could potentially result in product failing the ASTM D1655 specification of 0.10 mgKOH/g maximum. The sparged samples themselves exceed European Def Stan 91-91 limits of 0.015 mgKOH/g maximum.

7.6 ADDITIONAL TESTS
Vapor Phase

The observation that a significant amount of light hydrocarbons were still present in jet fuel following manufacture was confirmed by a further experiment. A second sample of jet fuel was sparged with nitrogen as in Section 3 and the vapor phase analysed by GC-Mass Spectrometry. The spectra confirmed the species present, Table 7-5. Benzene concentration was significantly lower on a pro-rata basis compared to the previous samples, possibly indicating a link with the original crude oil used to manufacture the fuel.

Gas Entrained in Fuel

Following the experiment where carbon dioxide was sparged into the fuel, it was observed that a sample stored in a one liter can was under pressure. A further simple experiment was undertaken to investigate this effect. One liter samples of base fuel were sparged through the liquid phase with nitrogen and carbon dioxide for ca. 20 minutes. A sample of fuel was taken for vapor pressure determination using standard industry apparatus (ASTM D5191). In addition, each fuel was subjected to low pressure utilizing a vacuum line and any unusual effects observed.

Results were determined as:

	DVPE kPa	Observations under nominal vacuum
Base fuel.	0.9	No gas bubbles.
Base fuel following nitrogen sparge through liquid.	1.7	Few gas bubbles in liquid.
Base fuel following carbon dioxide sparge through liquid.	17.6	Many gas bubbles in liquid.

Results suggest that fuels sparged with carbon dioxide have the potential to solubilize a significant amount of gas. This is later released when the fuel experiences lower pressure/higher temperature. The vapor pressure of the fuel is also increased to a level typical of jet B/wide-cut aviation fuel. Nitrogen gives a similar, but much lower, effect.

Literature [1,2] data for the solubility of the two gases in hydrocarbons support these observations:

1 atm, 25 °C	n-Octane	n-Nonane	n-Decane
Nitrogen g/kg Hydrocarbon ml/kg Hydrocarbon*	0.327 262	0.287 230	0.247 198
Carbon Dioxide g/kg Hydrocarbon ml/kg Hydrocarbon*	4.648 2366	4.845 2467	5.567 2834

* Assuming ideal gas at standard temperature and pressure

Given the known risk to safety from vapor bubbles forming in aircraft fuel systems, for example through the use of jet B, this effect is important and warrants further investigation.

Thermal Stability

Removal of oxygen from jet fuel by sparging with an inert gas may have the potential to increase jet fuel thermal stability. A limited test was undertaken to examine this effect using a fuel of JFTOT rating 3 'Abnormal, Peacock'. The fuel was sparged with nitrogen for a period of 40 minutes as detailed in Section 3. JFTOT was then determined with no air sparge:

	Reference	JFTOT
Base fuel	W01/046	3AP
Nitrogen into liquid phase	W01/048	>4P
Nitrogen above liquid phase	W01/050	4P

Thus, for the sample of jet fuel tested, the thermal stability was not improved following nitrogen sparge.

7.7 CONCLUSIONS

Vapor Phase

- The vapor phase above jet fuel contains a proportion of light hydrocarbons which have become entrained in the fuel during manufacture.

- When recovered and liquefied, the vapor phase hydrocarbons form a highly flammable, volatile mixture of low flash point unlike the original jet fuel but similar to motor gasoline.

- Benzene may be concentrated to such an extent in the recovered vapor to render the liquefied product carcinogenic (>0.1% benzene).

- In the case of nitrogen, passing gas through the fuel gave a greater concentration of hydrocarbons in the vapor phase than passing gas over the fuel. Some time dependence was observed which might require further investigation.

- Based on the results, a large aircraft receiving 200,000 liters of fuel could potentially emit about 4 kg of hydrocarbon vapor for recovery.

Liquid Phase

- No significant effect on product quality, using standard test methods, was observed following exposure of fuel to nitrogen.

- An increase in fuel acidity (≥+0.041 mgKOH/g) was observed following exposure of fuel to carbon dioxide. The resultant fuel failed European Defence Standard specifications of 0.015 mgKOH/g maximum.

- Additional tests indicated the vapor pressure of the fuel increased when gases had been sparged through the liquid. Nitrogen and carbon dioxide sparge resulted in a +0.8 kPa and + 16.7 kPa rise in fuel vapor pressure respectively. On exposure to low pressure, both fuels exhibited the formation of gas bubbles in the liquid phase. Given the risk to safety from vapor formation in aircraft fuel systems, this effect warrants further investigation.

References

[1] Makranczy, J; Megyery-Balog, Mrs. K; Rusz, L.; Patyi, L; Hung. J. Ind. Chem. <u>1976</u> 4(2), 269-280.

[2] Tong Jingshan; Gao Guanghua; Wang Xiagong; Qinghua Dazue Xuebao <u>1988</u>, 28(3), 28-32.

	Gas through liquid phase		Gas over liquid phase	
	20 minutes **W01/073** **mg/liter**	**40 minutes** **W01/074** **mg/liter**	**20 minutes** **W01/075** **mg/liter**	**40 minutes** **W01/076** **mg/liter**
C3	0.1	0.1	0	0
C4	0.2	0.5	0.2	0.2
C5	0.6	1.2	0.6	0.6
C6	1.8	3.7	1.8	1.5
C7	2.7	5.5	2.3	2.6
Benzene	0.3	0.5	0.2	0.2
C8	1.8	5.1	2.6	3.3
Toluene	0.6	1.2	0.2	0.4
TOTAL*	8.1	17.8	8.1	8.9

Table 7-1. Vapor Analysis, Nitrogen Sparge 21°C

	Gas through liquid phase		Gas over liquid phase	
	20 minutes **W01/091** **mg/liter**	**40 minutes** **W01/092** **mg/liter**	**20 minutes** **W01/093** **mg/liter**	**40 minutes** **W01/094** **mg/liter**
C3	0.1	0.1	0	0
C4	0.2	0.3	0.2	0.1
C5	0.6	0.6	0.6	0.4
C6	1.7	1.8	1.4	1.2
C7	2.3	2.4	1.9	1.8
Benzene	0.2	0.2	0.2	0.2
C8	2.0	2.3	1.9	1.7
Toluene	0.4	0.5	0.4	0.3
TOTAL*	7.5	8.2	6.6	5.7

• Total excludes trace components >C8 carbon number which were not determinable.

Table 7-2. Vapor Analysis Carbon Dioxide Sparge 21°C

ANALYSIS	Base Fuel	Base fuel after 40 minute N$_2$ sparge through liquid	Base fuel after 40 minute N$_2$ wash over liquid	UNITS
D1319 FIA Aromatics	17.7	17.7	18.1	% v/v
D1322 Smoke point	25.0	25.0	25.0	mm
D3338 Specific Energy	43.256	43.257	43.245	MJ/kg
D381 Existent Gum (Steam)	<1	<1	<1	mg/100ml
D3948 WSIM (microsep)	83	93	79	-
IP365 Composite Density	798.7	798.7	798.7	kg/m^3
D4294 Sulfur	<0.01	<0.01	0.01	% m/m
D86 Initial Boiling Point	149.9	150.3	147.7	°C
D86 05 % Recovered	162.9	162.7	162.4	°C
D86 10 % Recovered	166.3	166.7	166.1	°C
D86 20 % Recovered	171.9	172.2	171.4	°C
D86 30 % Recovered	177.8	178.3	177.8	°C
D86 40 % Recovered	184.3	184.1	183.9	°C
D86 50 % Recovered	190.9	191.1	190.9	°C
D86 60 % Recovered	198.4	198.5	198.3	°C
D86 70 % Recovered	206.9	207.0	206.9	°C
D86 80 % Recovered	217.1	217.1	217.0	°C
D86 90 % Recovered	230.5	230.5	230.5	°C
D86 95 % Recovered	241.6	241.7	241.7	°C
D86 Final Boiling Point	258.8	260.9	257.9	°C
D86 Loss	0.4	0.3	0.7	% v/v
D86 Recovery	98.4	98.4	98.3	% v/v
D86 Residue	1.2	1.3	1.0	% v/v
IP16 Freeze point	-58.0	-57.2	-57.2	°C
IP154 Copper Corrosion 2Hrs @100 °C	1A	1B	1B	-
IP170 Flashpoint	40.5	40.0	40.0	°C
IP274 Conductivity	175	125	117	
IP274 Temperature	20	22	22	°C
IP289 Water Reaction Interface Rating	1B	1B	1B	-
IP30 Doctor Test	N	N	N	-
IP323 JFTOT Pressure Difference	0	0	0	mmHg
IP323 JFTOT Visual tube rating	1	1	1	-
IP354 Total Acidity	0.006	0.006	0.006	mg KOH/g
KV at -20 °C	3.482	3.451	3.464	cSt

Table 7-3. Jet Fuel Inspection Data, Nitrogen Sparge 21°C

ANALYSIS	Base Fuel	Base fuel after 40 minute CO$_2$ sparge through liquid	Base fuel after 40 minute CO$_2$ wash over liquid	UNITS
D1319 FIA Aromatics	17.7	18.1	17.5	% v/v
D1322 Smoke point	25.0	24.0	24.0	mm
D1840 Naphthalenes		1.55	1.88	% v/v
D3338 Specific Energy	43.256	43.244	43.252	MJ/kg
D381 Existent Gum (Steam)	<1	1	0	mg/100ml
D3948 WSIM (microsep)	83	92	91	-
IP365 Composite Density	798.7	799.0	799.1	kg/m^3
D4294 Sulfur	<0.01	<0.01	0.01	% m/m
D86 Initial Boiling Point	149.9	148.2	148.2	°C
D86 05 % Recovered	162.9	162.2	161.9	°C
D86 10 % Recovered	166.3	165.5	165.6	°C
D86 20 % Recovered	171.9	171.9	172.2	°C
D86 30 % Recovered	177.8	178.1	177.4	°C
D86 40 % Recovered	184.3	184.2	184.0	°C
D86 50 % Recovered	190.9	190.8	191.0	°C
D86 60 % Recovered	198.4	198.7	198.7	°C
D86 70 % Recovered	206.9	207.2	207.1	°C
D86 80 % Recovered	217.1	217.2	217.0	°C
D86 90 % Recovered	230.5	230.5	231.2	°C
D86 95 % Recovered	241.6	242.6	243.7	°C
D86 Final Boiling Point	258.8	257.8	257.8	°C
D86 Loss	0.4	0.7	1.0	% v/v
D86 Recovery	98.4	98.1	97.8	% v/v
D86 Residue	1.2	1.2	1.2	% v/v
D5901 Freeze point	-58.0	-57.2	-57.3	°C
IP154 Copper Corrosion 2Hrs @100 °C	1A	1A	1A	-
IP170 Flashpoint	40.5	40.5	41.0	°C
IP274 Conductivity	175	120	118	
IP274 Temperature	20	22	22	°C
IP289 Water Reaction Interface Rating	1B	1B	1B	-
IP30 Doctor Test	N	N	N	-
IP323 JFTOT Pressure Difference	0	0	0	mmHg
IP323 JFTOT Visual tube rating	1	1	1	-
IP354 Total Acidity	0.006	0.066	0.047	mg KOH/g
KV at -20 °C	3.482	3.441	3.435	cSt

Table 7-4. Jet Fuel Inspection Data, Carbon Dioxide Sparge 21°C

Component	W01/050 Relative Amount
Isobutane	4.9
n-Butane	10.2
Pentanes	37.1
Hexanes	10.8
Methylcyclopentane	1.9
Benzene	<0.6
Heptanes	4.9
Methylcyclohexane	5.9
Toluene	4.0
Octanes	12.4
Ethylcyclohexane	1.9
Xylenes	2.5
Nonanes	3.1
Decanes	0.6

Table 7-5 GC-Mass Spectrometry Analysis of Vapor Recovered From Jet Fuel Sparged With Nitrogen

ADDENDUM 2
TEXACO INC. LABORATORY REPORT

The following is a final summary report with results of the testing conducted here at Beacon for the ARAC Steering Committee. Also attached are the original reports of the two sets of experiments as Attachments A and B and the gas chromatography studies as Attachments C and D.

The initial set of experiments involved sparging nitrogen through a flask containing commercial jet A fuel. The flask was closed with a stopper and vapors were allowed to escape through a glass tube. Details may be found in Attachment A.

The second set of experiments independently included both closed flask and open cylinder testing. The closed flask set up simulated the interior of a closed tank (and replicated the first experiments), and the open cylinder was a more scientific approach to study the effects of the fuel after bubbling nitrogen through it, but allowing virtually all gases to escape from the container (minimum condensation). Details of this work may found in Attachment B.

Despite the various experimental arrangements and conditions, results indicated there was little or no change to properties tested for compliance with ASTM D 1655, Standard Specification for Aviation Turbine Fuels. However, in the second experiment, visual observations of the open cylinder and analysis of the fuel by gas chromatography (GC) clearly indicated the loss of lighter components from the base fuel. This report, attached as Attachment C, elaborates on the techniques used to arrive at the GC results.

As noted in Attachment B, several samples from each condition were taken and GC analysis was repeated on each sample. This provided confidence in the final analysis and helped to identify any outliers in the data set. Because of the distribution of hydrocarbon species, the fuel was segmented into groups based on the molecular weight (carbon number) of the components. It was determined that by separating the fuel into four groups, the analysis could be simplified while still retaining the accuracy required for statistical significance.

The groups were identified as:

1. C6-C10 alkanes and C1-C3 alkyl substituted cyclohexanes;

2. C11-C14 alkanes and C4-C7 alkyl substituted cyclohexanes;

3. C15-C16 alkanes and C8-C9 alkyl substituted cyclohexanes;

4. C17-C20 alkanes and C10 alkyl substituted cyclohexane.

Chromatographic subtraction was used to facilitate the analysis. For each hydrocarbon group, the areas under the peaks were measured or calculated at the before-sparging and after-sparging conditions then compared to each other. The differences were considered to be the losses attributed to outgassing and kinetic expulsion of lighter ends from the base fuel during sparging. Because the hydrocarbon molecular weight distribution within the fuel varied from C6 to C20 alkanes and from C1 to C10 alkyl substituted cyclohexanes, it was necessary to develop specific scales for each hydrocarbon group so that areas could be determined accurately. Chromatographs that typify the results are included as Appendix C.

As noted in the report, the commercial jet fuel (as purchased from the airport) consisted of 10 volume percent (vol%) of the lightest material (Group 1), 40 vol% moderate material (Group 2), 40 vol% heavier material (Group 3), and 10 vol% heaviest material (Group 4). As expected, most of the hydrocarbons displaced by scrubbing came from Group 1 with lesser amounts being lost as molecular weight (and group number) increased. There was no loss of hydrocarbon from the heaviest group. The volumetric loss determined by GC analysis was corroborated with visual inspection of the open cylinder. Details of the study are contained within Attachments B and C.

At your request, a second analysis to quantify and qualify aromatic loss from the base fuel was performed on the retained samples from the previous experiments. This analysis was conducted using a double-column GC, the results of which are attached as Attachment D.

ATTACHMENT A

2 sub-samples of commercial jet fuel (Jet A) were sparged with gaseous nitrogen, then subjected to full ASTM D 1655 testing and analysis by gas chromatography (GC). A third sub-sample (the unsparged airport sample) was also analyzed using these techniques so that results could be compared.

Attachment A1 contains the properties listed in Table 1 of ASTM D 1655, Standard Specification for Aviation Turbine Fuels (Volume 05.01, Annual Book of Standards, 2000). In addition to the requirements of Table 1, Attachment A1 also contains all ASTM D 1655 test results and other pertinent information. Where duplicate runs were made (density and net heat of combustion) an additional line was added and both results are reported.

To facilitate the experiment and based on laboratory requirements for testing, commercial jet fuel was purchased locally and stored in a laboratory at 70ºF ambient temperature.

Set-Up: A 4000 milliliter (mL) sub-sample was placed in a 4000 mL flask and a sparger was inserted so that it just cleared the bottom of the flask. Gaseous nitrogen with a purity of 99.999% (maximum moisture = 1 ppm, maximum oxygen = 1 ppm, maximum hydrocarbon content = 0.5 ppm) was used throughout the experiment, and was regulated to flow 350 mL/minute. Using Tygon® tubing, the 4000 mL flask was attached to a 250 mL condensing flask which was partially submerged in liquid nitrogen. The condensing flask was connected to another 250 mL flask which was vented into the hood through a water bath. Although liquid was captured in the condensing flask, it was not possible to extract it without immediate vaporization; thus no analysis could be made of the condensate. Following the initial 20 minute sparging phase, a small sample was taken for gas chromatography and approximately 2000 mL was poured into two separate containers for ASTM D 1655 tests. The sparger was replaced and the experiment was continued for an additional 1 hour 40 minutes. At that time the nitrogen flow was stopped, another small sample was taken for gas chromatography, and the remaining fuel was transferred to two separate containers to await ASTM D 1655 testing. The experimental apparatus is shown in Attachments A2 and A3.

Observations/Conclusions: among the three samples (Airport, 20 Minute Sparge, 120 Minute Sparge) most ASTM D 1655 test results varied little or none from each other. However, density and heat of combustion values changed measurably between samples from the sparging process, and the samples were re-tested about two days after the original tests to verify the differences. Interestingly, the re-runs indicated now consistent, albeit different than the original, results across the three samples. This was in direct conflict with the earlier results and caused a great deal of apprehension among those working on this project. It is hypothesized that immediately following sparging the fuel/ullage is in a state of non-equilibrium (during outgassing) and that after some period of time the fuel/ullage equilibrates. Depending on the composition of the vapors, this could explain the changes in both density and heat of combustion, and their eventual (and inevitable) return to a state of equilibrium. The second experiment will be designed to investigate these possibilities. It should also be noted that although the gas chromatography analysis is incomplete at this writing, the chromatographs indicate obvious changes to the composition of the fuel during sparging. It is hoped that the GC identification of the hydrocarbon species driven out of the fuel during sparging will corroborate the differences observed in density and heat of combustion.
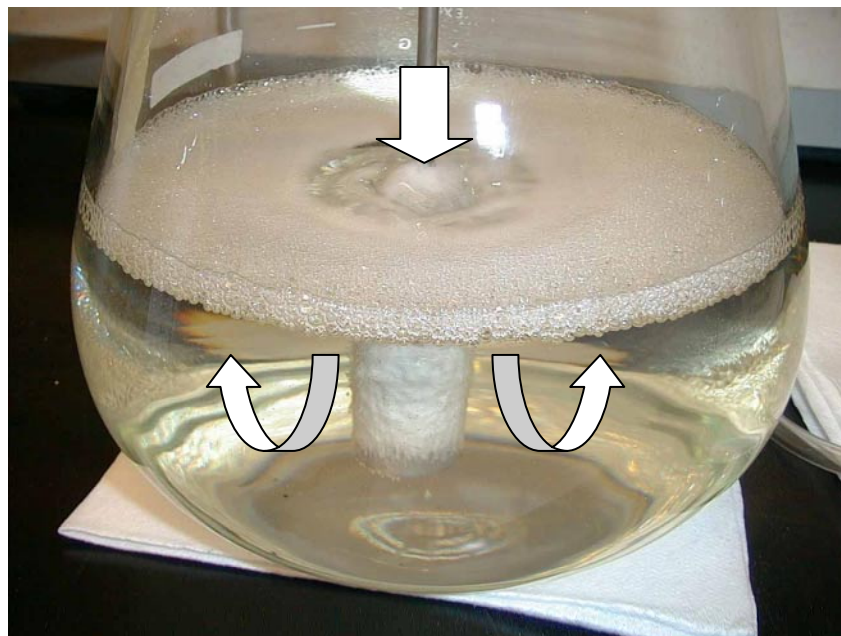
Attachment A1

Detailed Requirements for ASTM D 1655, Jet A Fuel						
Property			**Sample**			
(January 23, 2001)				**20 Minute N$_2$**	**120 Minute N$_2$**	
			Airport	**Sparging**	**Sparging**	**Test**
		D 1655	**ID 3342**	**ID 3343**	**ID 3344**	**Method**
COMPOSITION						
Acidity, total mg KOH/g	max	0.10	n/a	n/a	n/a	
Aromatics, vol %	max	25	20.0	20.2	19.9	
Sulfur, mercaptan, weight %	max	0.003	n/a	n/a	n/a	
Sulfur, total weight %	max	0.30	0.085	0.085	0.086	XRF
VOLATILITY						
Distillation temperature, ^{o}C:						D 86
Initial boiling point, temperature		n/a	168.1	168.4	169.3	
5% recovered, temperature		n/a	182.7	181.5	182.3	
10% recovered, temperature	max	205	185.9	184.7	184.9	
20% recovered, temperature	max	…	194.3	193.0	194.2	
30% recovered, temperature		n/a	201.5	200.4	200.9	
40% recovered, temperature		n/a	209.0	207.5	208.1	
50% recovered, temperature	max	report	216.6	215.3	216.0	
60% recovered, temperature		n/a	224.4	223.5	223.9	
70% recovered, temperature		n/a	233.3	232.5	232.9	
80% recovered, temperature		n/a	243.7	242.7	242.9	
90% recovered, temperature	max	report	256.9	256.0	256.2	
95% recovered, temperature		n/a	268.8	268.4	268.0	
Final boiling point, temperature	max	300	282.9	281.5	281.5	
Distillation residue, %	max	1.5	0.9	1.0	0.9	
Distillation loss, %	max	1.5	1.3	1.5	1.1	
Flash point, ^{o}C	min	38	51.0	51.5	51.5	D 56
Density at 15°C, kg/m^3		775-840	809.7	796.8	809.6	D 4052
API gravity			43.2	46.0	43.2	Conv.
Density, second run				809.6		D 4052
API Gravity, second run				43.2		Conv.
Vapor pressure, 38°C, kPa	max	…	19.2	7.1	10.1	Conv.
Vapor pressure, 38°C, psi			0.19	0.07	0.10	D 5191
FLUIDITY						
Freezing point, ^{o}C	max	-40	-43.8	-44.0	-44.0	D 5901
Viscosity -20°C, mm^2/s	max	8.0	n/a	n/a	n/a	
			1.41@40C	1.41@40C	1.41@40C	D 445
COMBUSTION						
Net heat of combustion, MJ/kg	min	42.8	47.825	46.120	45.930	D 4809
Net heat of combustion, 2nd Run			46.090	46.085	46.080	D 4809
Smoke point, mm	min	25				
CORROSION						
Copper strip, 2 h at 100°C	max	No. 1	1a	1a	1a	D 130
STABILITY						
Thermal:						
Filter pressure drop, mm Hg	max	25	0.1	0.1	0.0	D 3241
Tube deposit less than		Code 3	3	3	3	
CONTAMINANTS						
Existent gum, mg/100 mL	max	7	3	2	2	D 381
Water reaction:						
Interface rating	max	1b	1	2/1b	1b	
ADDITIVES						
Electrical conductivity, pS/m			n/a	n/a	n/a	

Attachment A2. Experimantal Apparatus
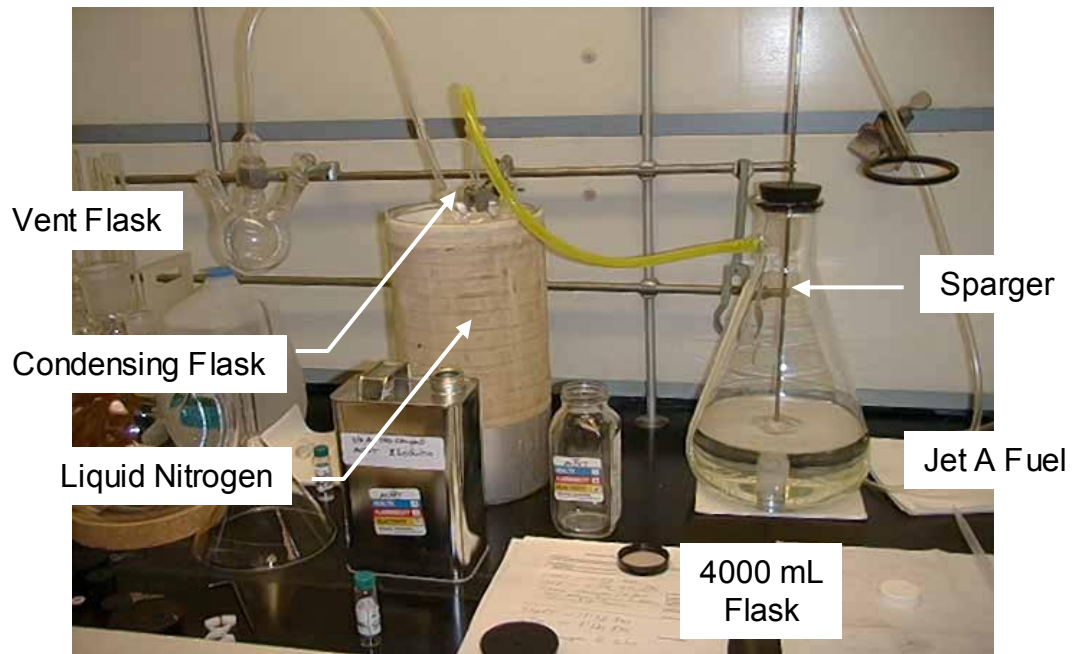
Experimental Apparatus

Attachment A3. Detail of Sparging in Closed Flask

ATTACHMENT B

Commercial jet fuel (Jet A) was scrubbed with gaseous nitrogen, then subjected to analysis by gas chromatography (GC), ASTM D 4052[1], and ASTM D 4809[2]. The physical tests were conducted based on results of previous testing (complete ASTM D 1655, Standard Specification for Aviation Turbine Fuels) of jet fuel from the same base source. In that experiment, it was determined that nitrogen scrubbing affected only density and heat content.

The experimental design is explained below, and Attachment B1 contains the results of ASTM D 4052 and ASTM D 4809. The same commercial jet fuel that was used for the first experiment was stored at 70ºF, and was also used for this experiment.

Design Set-Up, Closed Flask: A 4000 milliliter (mL) sub-sample was placed in a 4000 mL Erlenmeyer flask and a sparger was inserted so that it just cleared the bottom of the flask. The flask was placed in a laboratory hood with airflow of 166 cubic feet per minute with the front glass at 12 inches above the threshold. Gaseous nitrogen with a purity of 99.999%[3] was used throughout the experiment, and was regulated to flow 350 mL/minute at 120 kPa pressure. Using Tygon® tubing, the 4000 mL flask was attached to a 250 mL condensing flask, which was partially submerged in liquid nitrogen. The condensing flask was connected to another 250 mL flask, which was vented into the hood. Following the initial 20 minute sparging phase, a sample was drawn from the top, center of the flask with a pipette, and three 15 mL test tubes were filled with fuel and sealed with rubber stopples. Also, two 65 mL glass bottles were filled and sealed with plastic caps. To help determine whether stratification of the upper flask volume had occurred, the fuel in the flask was then stirred for approximately one minute until homogeneously mixed and then another sample was drawn and three additional test tubes and two additional bottles were filled and sealed. Two thousand milliliters were then removed from the flask to replicate the previous experiment. The sparger was replaced and the experiment was continued for an additional 1 hour 40 minutes. At that time the nitrogen flow was stopped and a sample was drawn from the top, center of the fuel in the flask with a pipette, and three 15 mL test tubes were filled with fuel and sealed with rubber stopples. Again, two 65 mL bottles were filled and sealed with plastic caps. The fuel in the flask was again stirred for approximately one minute until the fuel was homogeneously mixed and another sample was drawn and three additional test tubes and two additional bottles were filled and sealed. The closed-flask experimental apparatus is shown in Appendix B2.

Design Set-Up, Open Flask: A 325 milliliter (mL) sub-sample was placed in a 500 mL open cylinder and a sparger was inserted so that it just cleared the bottom of the cylinder. Gaseous nitrogen with a purity of 99.999%[4] was used throughout the experiment, and was regulated to flow 180 mL/minute at a pressure of 120 kPa. The top of the cylinder was completely open to the hood. As in the closed-flask experiment, the nitrogen scrubbing was conducted while in a laboratory hood that had an air flow of 166 cubic feet per minute with the front glass at 12 inches above the threshold. Following the initial 20 minute sparging phase, a sample was drawn from the cylinder with a pipette, and three 15 mL test tubes were filled with fuel and sealed with rubber stopples. Also, two 65 mL glass bottles were filled and sealed with plastic caps. The sparger was then replaced and the experiment was continued for an additional 1 hour 40 minutes. At that time the nitrogen flow was stopped and a sample was drawn from the cylinder with a pipette, and three 15 mL test tubes were filled with fuel and sealed with rubber stopples. Again, two 65 mL glass bottles were filled and sealed with plastic caps. The open cylinder experimental apparatus is shown in Appendix B3.

---

[1] ASTM D 4052: Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter
[2] ASTM D 4809: Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)
[3] Maximum moisture = 1 ppm, maximum oxygen = 1 ppm, maximum hydrocarbon content = 0.5 ppm
[4] Maximum moisture = 1 ppm, maximum oxygen = 1 ppm, maximum hydrocarbon content = 0.5 ppm

Observations/Conclusions: Based on results of ASTM D 4052 and D 4809, there appears to be virtually no change between unscrubbed base fuel, 20 minute scrubbed fuel, and 120 minute scrubbed fuel, whether scrubbing occurred in a closed flask (see Attachment B2), or open flask (see Attachment B3). These results also refute the possibility that significant stratification occurred at the top of the closed flask during sparging, because results from stirred and unstirred samples showed no differences. Although an exchange of gases or condensation and recombining of evaporated fuel with the base fuel (closed flask) may or may not have taken place, the bulk fuel properties (per ASTM D 4052 and D 4809) were not affected.

The density and net heat of combustion results (required in ASTM D 1655, Standard Specification for Aviation Turbine Fuels) indicated no changes to the fuel during scrubbing. However, visual examination of the cylinder and GC analysis of samples indicated a loss of approximately 4 mL (1.2 volume %) of fuel during scrubbing and a change in fuel composition attributed to this operation.

Gas Chromatography Analysis of Changes due to Nitrogen Scrubbing:

There are measurable, statistically significant changes in the chromatogram indicating that scrubbing at the rates used in the lab (180 mL/min, @ 120 kPa N_2,) drives off a portion of the fuel.

The speciation of which fractions and how much are being driven off is presented below:

- Alkanes   (C6–C12)
- Alkylcyclohexane   (C1-C5) substituted cyclohexane

With much less or no change in the higher molecular weight

- Alkanes   (C13-C20)
- Alkylcyclohexanes   (C6-C10) substituted alkyl cyclohexanes.

In addition heavier somewhat branched two ring aliphatic compounds showing little change.

Isoprenoids (substituted bicyclo C15 and C16 compounds) show little change.

The open cylinder experiment yielded the following distribution and loss:

From the 325 mL, open cylinder, 120 minute scrubbed sample the following changes were measured:

1. There is a 10% loss from scrubbing of the lightest fuel compounds (initially 10% of the AvJet A):
   (C6-C10 alkanes), and (C1-C3 alkyl substituted cycloalkanes) (1% of original 325 mL)

2. There is a 0.4% loss from scrubbing of the moderate weight compounds (initially 40% of the AvJet A):
   (C11-C14 alkanes) and (C4-C7 alkyl substituted cycloalkanes) (0.16% of original 325 mL)

3. There is a 0.1% loss from scrubbing of the heavier weight compounds (initially 40% of the AvJet A):
   (C15–C16 alkanes) and (C8-C9 alkyl substituted cycloalkanes) (0.01% of original 325 mL)

4. There is no loss from scrubbing of the heaviest weight compounds (initially 10% of the AvJet A):
   (C17-C20 alkanes) and (C10 alkyl substituted cycloalkanes)

Note: Based on the Gas Chromatography 3.8 mL out of 325 mL of fuel should be lost from the scrubbing.

Independent visual volumetric measurements of the remaining fuel in the cylinder indicated 4 mL (1.2 vol.%) of fuel was lost. This supports the Gas Chromatography work directly. The hydrocarbon distribution follows an exponentially decreasing loss with increasing carbon number:

Distribution of Hydrocarbon Types with Scrubbing
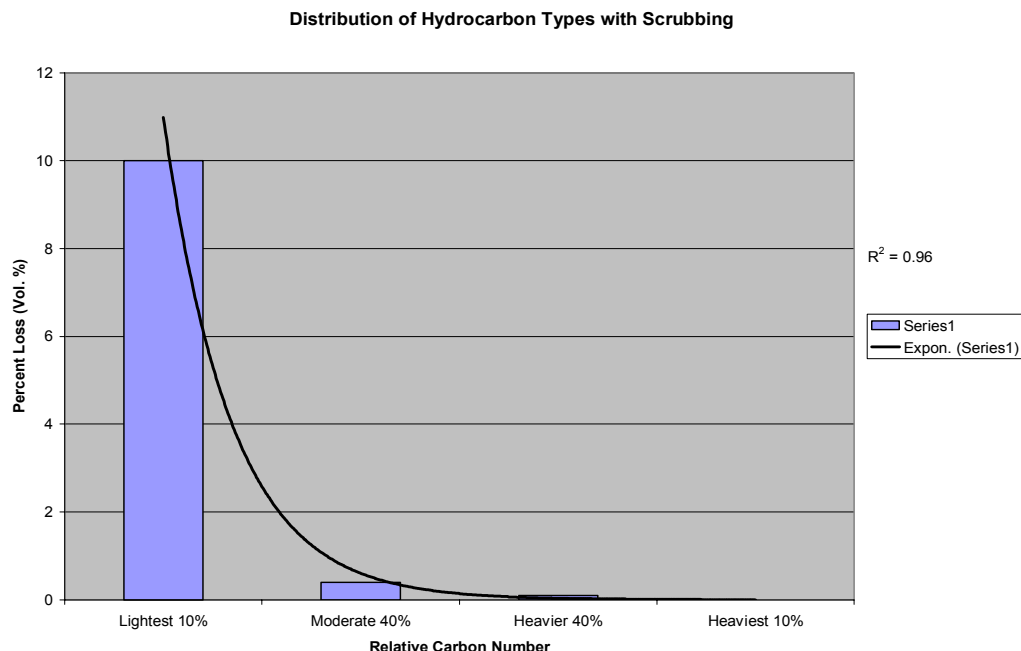
While results of the physical tests (ASTM D 4052 and D 4809) showed virtually no change to the "bulk" properties of the fuel, gas chromatography analyses clearly indicated changes to hydrocarbon distribution. Furthermore, the bulk properties are tolerant of this 1.2 volume % loss of boiling-point dependent hydrocarbons and their distribution within the fuel as illustrated in the figure above. However, the reader should take heed of the conditions under which these experiments were conducted. Note especially the flow and pressure of nitrogen, hood air flow, and quantities of fuel used. Although the fractions that were driven out of the fuel by nitrogen scrubbing could not be captured for analysis, the technique of chromatogram subtraction (as used here) is quite accurate and provides reliable insight as to the dynamic nature of these experiments.

Attachment B1

Sample ID	Description	ASTM D 4052	ASTM D 4809 (MJ/kg)
3450	Closed Flask, 20 Minute Sparge, Top	0.8095	46.1
3451	Closed Flask, 20 Minute Sparge, Top	0.8094	46.3
3452	Closed Flask, 20 Minute Sparge, Stirred	0.8095	46.0
3453	Closed Flask, 20 Minute Sparge, Stirred	0.8094	46.1
3454	Closed Flask, 120 Minute Sparge, Top	0.8095	46.1
3455	Closed Flask, 120 Minute Sparge, Top	0.8094	46.1
3456	Closed Flask, 120 Minute Sparge, Stirred	0.8095	46.0
3457	Closed Flask, 120 Minute Sparge, Stirred	0.8094	46.1
3458	Open Cylinder, 20 Minute Sparge	0.8093	46.1
3459	Open Cylinder, 20 Minute Sparge	0.8094	46.0
3460	Open Cylinder, 120 Minute Sparge	0.8094	46.2
3461	Open Cylinder, 120 Minute Sparge	0.8095	46.1
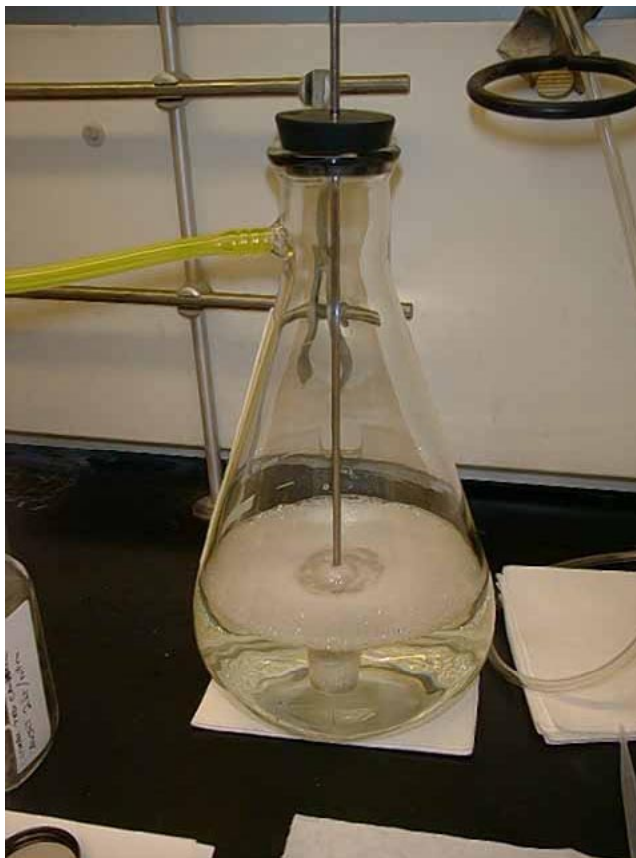
Attachment B2. Closed Flask With Sparger

Attachment B3. Open Cylinder With Sparger

ATTACHMENT C

Typical GC chromatograms: Jet A base fuel studied before and after 120 minutes of nitrogen scrubbing. The chromatogram with the higher peak heights (especially at early elution time and lower carbon no.) is that of the original starting fuel before scrubbing. As time increases the differences clearly diminish indicating the heavier components are not removed by the scrubbing.

Time (Minutes)
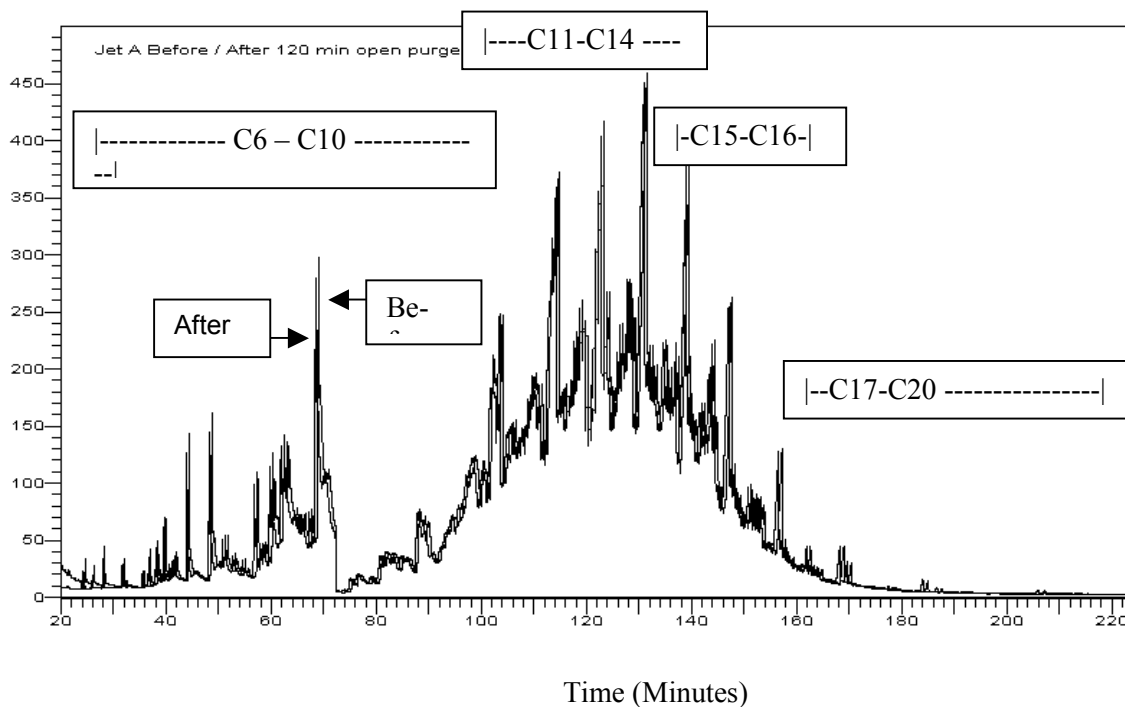
20 – 100 minutes, Group 1: C6-C10 alkanes and C1-C3 alkyl substituted cycloalkanes
100 –140 minutes, Group 2: C11-C14 alkanes and C4-C7 alkyl substituted cycloalkanes
140 – 160 minutes, Group 3: C15-C16 alkanes and C8-C9 alkyl substituted cycloalkanes
160 - 220 minutes, Group 4: C17-C20 alkanes and C10 alkyl substituted cycloalkanes

The experimental parameters include:
Varian model STAR 3600 Cx Gas Chromatograph
Using a Supelco 2-4160 PETROCOL DH 100 M x 0.25 mm and 0.5 micron film
1 microliter injection using a Hamilton # 7101 1 microliter syringe

Initial column Temp:	35 (C)
Initial column Hold time	15 minutes
Program 1 rate in degree (C) per minute	1.0
Program 1 hold time	20
Program 2 final column temp (C)	200
Program 2 rate in degree (C) per minute	2.0
Program 2 hold time	95
Injector Temp (C)	300
Detector Temp (C)	300
FID Attenuation	8
A two step ramp was used such that at 72.36 minutes the FID range changed from 8 to 11	
Total time	225 minutes

ATTACHMENT D

Retains from original fuel scrubbing experiments were reviewed to determine the concentration of benzene and toluene by a Gas Chromatography procedure developed to be more suitable for low concentrations of benzene in complex mixtures. The procedure includes:

- Increasing the sample size from 1 to 4 microliters

- Calculating benzene and toluene concentration based on:

  - The same GC experimental conditions for D3606

  - Varian Model 3700 Gas chromatograph

    - Column A: 8 m x 3.2 mm column with 10% (m/m) dimethylpolysiloxane in Chromosorb W, 60-80 mesh;
    - Column B a 4.6 m x 3.2 mm 20% (m/m) TCEP on Chromosorb P, 80 – 100 mesh.

The ratio of the integrated peak area of the analyte peak to that of the methyl-ethyl ketone internal standard peak.

Finding the relationship of analyte concentration to peak area ratio from measurements of a certified D3606 standard where the concentrations of the analytes (benzene and toluene) are known.

The results of these analyses are given in the table below:

Sample ID	Benzene		Toluene		% Removed	
	Vol. %	(ppm)	Vol.%	(ppm)	Benzene	Toluene
Basefuel Jet A	0.00575	(57.5)	0.108	(1080)	0.00	0.0
Closed Flask 20 min	0.00574	(57.4)	0.108	(1080)	0.17	0.0
Closed Flask 120 min	0.00569	(56.9)	0.108	(1080)	1.04	0.0
Open Cylinder 20 min	0.00475	(47.5)	0.100	(1000)	17.39	8.0
Open Cylinder 120 min	0.00465	(46.5)	0.100	(1000)	19.13	8.0

In general the Closed Flask scrubbing removes from a fraction at 20 minutes up to 1 percent at 2 hrs. In contrast, the Open Cylinder scrubbing removes 17% of the fuel's benzene in as little as 20 minutes, which increases to 19 % removal after 2 hrs. As we saw in the overall chemical emission case, the Closed Flask allows condensation back to the liquid.

8.0 ECONOMICS

Cost estimates were determined using the design concepts developed by the team and typical airport construction practices.

Figures 8-1 through 8-4 are economic evaluations of the inerting systems considered by the Working Group for each type of airport. The estimates used a standard form common to each estimate. The economic evaluation was broken into two parts, capital (non recurring)and operation (recurring) costs.

The evaluations include only the cost of construction and maintenance; operator labor costs are not included.

	Capital			
		Airport size		
Description	**Cost per mobile unit, K**	**Large**	**Medium**	**Small**
Number of mobile units		12	7	2
• System and truck	330	3960	2310	660
• Parking and site preparation	1	12	7	2
• Piping, hoses, reels, other	0	0	0	0
• Electrical power upgrades	0	0	0	0
• Engineering and soft costs (19%)	1	12	7	2
• Contingency (25%)	83	996	581	166
Total	415	4980	2905	830

	Operational costs per month			
		Airport size		
Description	**Cost per mobile unit, K**	**Large**	**Medium**	**Small**
Number of mobile units		12	7	2
• Rent at $1.0/ft	4	48	28	8
• Lease system if applicable	0	0	0	0
• System maintenance	1	12	7	2
• Power cost (if not already included)	2	24	14	4
• Maintenance and operation	.5	6	3.5	1
Total	7.5	90	52.5	15

Note: All figures are in thousands of U.S. dollars.

Figure 8-1. ARAC Facility Estimate—Mobile Ullage System

	Capital			
		Airport size		
Description	**Cost per concourse, K**	**Large**	**Medium**	**Small**
Number of concourses		9	2	NA
• System	0	0	0	—
• Site preparation	35	315	70	—
• Piping, hoses, reels, other	408	3,672	816	—
• Electrical power upgrades	500	4,500	1000	—
• Engineering and soft costs (19%)	179	1,613	358	—
• Contingency (25%)	281	2,525	562	—
Total	1,403	12,624	2806	NA

Notes:
• Concourse is 20 gates.
• All figures are in thousands of U.S. dollars.

Figure 8-2. ARAC Facility Estimate—Fixed Ullage System (Sheet 1 of 2)

Operational costs per month				
Description	Cost per concourse, K	Airport size		
		Large	Medium	Small
Number of concourses		9	2	NA
• Rent at $20/ft	2	18	4	—
• Lease system if applicable	0	0	0	—
• System maintenance	1	9	2	—
• Maintenance and operation	Per Airport	25	13	—
Total		52	19	NA

Note: All figures are in thousands of U.S. dollars.

Figure 8-2. ARAC Facility Estimate—Fixed Ullage System (Sheet 2 of 2)

Capital				
Description	Cost per tank, K	Airport size		
		Large	Medium	Small
Per tank at one fuel facility		20	4	2
• System	0	0	0	0
• Site preparation	20	400	80	40
• Piping, hoses, reels, other	101	2,014	403	201
• Electrical power upgrades	30	600	120	60
• Engineering and soft costs (19%)	29	573	115	57
• Contingency (25%)	45	897	179	90
Total	224	4,483	897	448

Operational costs per month				
Description	Cost per gal/ min delivered, K	Airport size		
		Large	Medium	Small
Thousands of gallons per minute		4.5	1.0	0.4
• Rent at $1.0/ft	2	7	2	1
• Lease system if applicable	1	2	1	0
• System maintenance	1	5	1	0
• Inert gas cost	26	117	26	10
• Power cost (if not already included)	0	0	0	0
• Maintenance and operation	2	9	2	1
Total	31	140	31	12

Note: All figures are in thousands of U.S. dollars.

Figure 8-3. ARAC Facility Estimate—Fixed Scrubber System

Capital				
Description	Cost per truck, K	Airport size		
		Large	Medium	Small
Number of existing refuelers		14	9	4
• System and truck	8	112	72	32
• Parking and site preparation	0	0	0	0
• Piping, hoses, reels, other	0	0	0	0
• Electrical power upgrades	0	0	0	0
• Engineering and soft costs (19%)	0	0	0	0
• Contingency (25%)	2	28	18	8
Total	10	140	90	40

Figure 8-4. ARAC Facility Estimate—Mobile Scrubber System (Sheet 1 of 2)

Operational costs per month				
		Airport size		
Description	**Cost per truck, K**	**Large**	**Medium**	**Small**
Number of refuelers		14	9	4
• Rent at $1.0/ft	0	0	0	0
• Lease system if applicable	0	0	0	0
• System maintenance	1	7	5	2
• Inert gas cost	0	0	0	0
• Power cost (if not already included)	1	7	5	2
• Maintenance and operation	1	7	5	2
Total	2	21	14	6

Note: All figures are in thousands of U.S. dollars.

Figure 8-4. ARAC Facility Estimate—Mobile Scrubber System (Sheet 2 of 2)

8.1 ESTIMATE LEGEND AND LINE ITEM EXPLANATIONS

General

The estimates for each type of airport and each CONCEPT estimated used a form that is common to each estimate. The form was broken into two pieces, CAPITAL and OPERATION

CAPITAL: Capital costs are those outlays made to design, install and commission a system (CONCEPT). Included in the CAPITAL estimates are (1) System/Truck costs, (2) Parking and Site Prep costs, (3) Piping, hoses and reels for fixed systems, (4) Electrical Power upgrades, (5) Engineering and soft costs, (6) Contingencies.

OPERATION: Monthly operational costs are those outlays necessary to operate the system (CONCEPT) and are exclusive of capital costs. Depreciation is ignored. Included in the OPERATION estimates are (7) Rent, (8) System (CONCEPT) lease, (9) System (CONCEPT) maintenance, (10) Inert gas costs for delivered (not generated) gas, (11) Power costs (if not already included in other line items, and (12) Maintenance and Operation costs.

Each 'outlay' is defined for reference below:

1. SYSTEM/TRUCK COSTS

   a) Generators

   b) Storage Tanks LN_2

   c) Controls

   d) Power, Lights and Distribution from Supply (See Item 4 for electrical supply infrastructure)

   e) System Enclosure (if any)

   f) Rolling Equipment (if applicable)

2. PARKING AND SITE COSTS

   a) Fence

   b) Rooms / Walls / etc.

   c) Site Lighting

   d) Ramp Striping

   e) Barricades

3. PIPING / HOSES / REELS / ETC. FOR FIXED SYSTEMS (CONCEPTS)

   a) Piping

   b) Hoses

   c) Gate Distribution elements to aircraft

4. ELECTRICAL POWER UPGRADES

   a) Utility Sets a New Service

   b) New Supply Switch board

   c) Space Costs / New Electrical Room

5. ENGINEERING and SOFT COSTS

   a) Design   6 %

   b) Construction Administration   3 %

   c) Program Management   6 %

   d) Construction Management   3 %

   e) Permit and related costs   1 %

   f) Infrastructure Survey $25,000 each Concourse

   g) Subtotal   19 % + $25,000

6. CONTINGENCIES in CAPITAL BUDGET

   a) Unforeseen conditions

   b) Conceptual Unknowns

7. RENT

   a) Lease for Concourse space @ $20/yr

   b) Lease for Site space @ $1/month per foot

8. SYSTEM LEASE COST

   a) Inert Gas Generating System Lease cost (if applicable)

9. SYSTEM MAINTENANCE

   a) Inert Gas Generating System maintenance costs by manufacturer (if applicable)

10. INERT GAS COSTS

    a) Delivery Costs

    b) Capitalized System Cost

    c) Gas Cost

    d) Back-up Gas costs

    e) Power/energy for System

    f) Depreciation of System (if manufacturer builds this in)

11. POWER COSTS

    a) Monthly power costs to run the system (if not built in to other line items)

12. AIRPORT MAINTENANCE & OPERATION

    a) Labor to maintain Metering, Piping / Connections, etc.

    b) Labor to Operate @ $22.00/hr.

    c) Space Parts

    d) Accounting

    e) Testing and Airport Certification

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

Based on the work performed the team reached the following conclusions:

Ground-Based Inerting

Supplying NEA for ground-based inerting is technically possible. It was beyond the task of this team to do a full analysis to determine if GBI was practical from a cost/benefit standpoint. Large and medium airports would use a fixed system supplemented with mobile equipment for remote operations. Small airports would be served with mobile equipment. Each airport is unique and the systems would have to be custom designed. This could impact the overall cost.

Gas Supply

Gaseous NEA generated using Air Separation Modules (ASM) would be the most practical gas to use for GBI due to the ability to make it on-site. This reduces the labor and costs associated with the delivery and storage of other gases. Cryogenic liquid nitrogen may have some limited application such as remote inerting of large transport category aircraft.

Fuel Scrubbing

The purpose of delivering nitrogen-saturated fuel into the airplane during normal fueling and refueling operations is to minimize the outgassing of entrained oxygen during the takeoff, climb, and cruse flight envelope to supplement the benefit of ground-based inerting. Because of the potential impact on fuel properties, the complexity of the processes required, and the costs the team concluded that fuel scrubbing was not practical. Fuel scrubbing adds nothing to the protection of the empty CWT.

Fuel Cooling

Fuel cooling does not by itself address the issue of the empty CWT. While fuel cooling will reduce fuel tank flammability, it will only do so in those tanks that have fuel added. It still requires a means of providing an inert gas for ullage washing the empty tanks. This will add to the cost and therefore it was concluded that fuel cooling was not feasible for the purpose of this study.

Standards

A global standard would need to be developed for the components of the system systems that interface with the aircraft, i.e. connections, metering systems, pressure control, safety system, etc. There would also need to be standards for the mobile equipment.

9.2 RECOMMENDATIONS

The AFT recommends that the FAA continue to research ways to supply NEA to the aircraft. Specifically, they should build a pilot plant that closely simulates the conditions that would occur in actual use. They should also research the use of liquid NEA to remotely inert the large transport category aircraft.

Appendix F

Airplane Operation and Maintenance

Task Team Final Report

This page intentionally left blank.